Cold Molecular Gas Halo at $z \sim 6$ with ngVLA

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Abstract

The Next Generation Very Large Array (ngVLA) will open the window for low-J CO line observations and provide us with the robust measurement of the total molecular gas mass over the circum-galactic medium (CGM) scale, where recent ALMA observations unveil the existence of the metal-enriched cold gas halo at $z \sim 6$. In this memo, we present mock observations results for the CGM-scale CO(2-1) halo at $z \sim 6$ with ngVLA. We find that the CO(2-1) halo at $z \sim 6$ is sufficiently recovered up to a radius of ∼15-kpc scale with a moderate integration time, which does not exceed the required integration time to detect the [C II] halo with ALMA more than a factor of several. Given the limited knowledge of the low-J CO line properties at $z > 5$ among moderately star-forming galaxies (e.g., star-formation rate $\lesssim 500\ M_\odot$ yr^{-1}), it is required to increase the sample size of the low-J CO line detection and test its realistic feasibility before the era of ngVLA. Bright Lyman-break galaxies and strongly lensed objects at $z > 5$ identified in recent surveys are the promising targets to achieve it.

Key words: Galaxy evolution — Circumgalactic medium — High-redshift — Outflow

1. Introduction

Recent ALMA studies unveil the existence of the cold gas halo emitting [C II] 158 μm line beyond the inter-stellar medium (ISM) of the central galaxies and spread over the circum-galactic medium (CGM; $\gtrsim$ 5–10 kpc) scale at $z \sim 6$ (Fujimoto et al. 2019; Fujimoto et al. 2020; Ginolfi et al. 2020; Herrera-Camus et al. 2021) (Figure 1). Given the first-generation of galaxies formed in high-density peaks of primordial gas, the existence of the CGM-scale metal-enriched gas is evidence of the outflow activities in the early universe. Studying the CGM scale metal-enriched gas in the early universe is thus an important probe to understand the outflow mechanisms that regulate the early galaxy formation and evolution.

To understand the outflow mechanisms, the outflowing gas mass is one of the critical quantities. Except for molecular hydrogen, the most abundant molecule, CO, has been commonly used in observations to probe the cold molecular gas (e.g., Carilli & Walter 2013 for a review). Among the rotational transition of CO, the low ground state transition, CO(1-0) and CO(2-1) traces the most diffuse and massive gas reservoir in and around galaxies, while higher-J transitions probe sequentially denser environments. The observed frequencies of these low-J CO lines cannot be covered with the current facilities (e.g., VLA) at $z > 3$, where the Next Generation Very Large Array (ngVLA) will open the window for these low-J CO lines. This indicates that ngVLA will offer us an invaluable opportunity to unveil the cold molecular gas view in the CGM-scale halo and constrain the outflow gas mass even at $z \sim 6$ via the low-J CO observations.

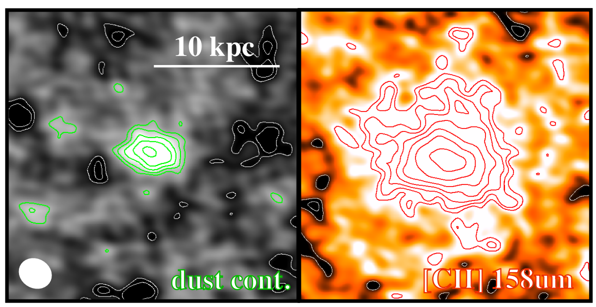

Fig. 1. Extended [C II] halo structure appeared around 18 star-forming (SFR∼10–70 $M_\odot$ yr^{-1}) galaxies at $z = 5 - 7$ via the visibility-based stacking (Fujimoto et al. 2019). The natural-weighted field image of the dust continuum and [C II] line are shown in the left and right panel, respectively. Contours start at $\pm 2\sigma$ and increases by a factor of $\sqrt{2}$. The synthesized beam is presented at the bottom left.

In this memo, we investigate the ability of ngVLA to detect the low-J CO halo around star-forming galaxies at $z \sim 6$. Section 2 outlines the simulation setup of mock ngVLA observations for the low-J CO halo at $z = 6$, and we report the mock observation results in Section 3. In Section 4, we discuss the time efficiency compared with ALMA and what is required before the era of ngVLA. A summary is presented in Section 5.

2. Simulation setup

2.1. Target

Aside from dusty starburst populations (star-formation rate, SFR $\gtrsim 500\ M_\odot\ \mathrm{yr}^{-1}$; e.g., Riechers et al. 2013), there has been only one and zero reports of the CO(2-1) and CO(1-0) line detection so far, respectively, among star-forming galaxies at $z > 5$. The CO(2-1) line has been detected in Hz10 at $z = 5.65$ with SFR $\sim 100\ M_\odot\ \mathrm{yr}^{-1}$ and the stellar mass M_star of $\sim 3\times10^{10} M_\odot$ (Pavesi et al. 2018). We thus target the CO(2-1) line as the first step and adopt the same source redshift and total CO(2-1) luminosity as Hz10 in the following analysis.

2.2. Spatial distribution of CO Halo

Because of the lack of deep observation results that sufficiently provide the spatial distribution of the CO(2-1) line from the star-forming galaxies at $z > 5$, we model the surface brightness profile of the CO(2-1) line from the recent deep [C II] observation results. In Fujimoto et al. (2019), the average of 18 star-forming galaxies at $z = 5-7$ via the ALMA visibility-based stacking shows the extended [C II] line structure up to a radius of the ∼10-kpc scale, which cannot be explained only by a single Sérsic profile. Alternatively, the two (= ISM + Halo) component fitting reproduces the surface brightness profile, including the extended structure, very well and suggests that the average profile has the effective radii of ∼1 kpc and 5 kpc, for the ISM and Halo component, respectively. We assume that the surface brightness profile of the CO(2-1) line is the same as the [C II] line that consists of the ISM and Halo components with effective radii of $r_\mathrm{e,ISM} = 1$ kpc and $r_\mathrm{e,Halo} = 5$ kpc, respectively, contributing to the total brightness equally.

We note that it is still unclear that there exists a cold molecular gas halo which is emitting the low-J CO line around the star-forming galaxies at $z \sim 6$, albeit the existence of the [C II] halo, albeit the little variation of the radial [C II] and CO line ratio in the Milkey Way (Pineda et al. 2013). To understand how differently the spatial distributions will be observed if the CO halo does not exist, we also model another surface brightness profile composed only of the ISM component. In the right panel of Figure 2, we show our model for the surface brightness profile of the CO(2-1) line.

2.3. Observation setup

To obtain mock observation maps, we use the CASA task SIMOBS by utilizing the ngVLA configuration file[1]. We choose the plain+core configuration with a total of 168 antennas composed of 94 core stations and 74 antennas included in the five spiral arm pattern. At the observed frequency of the CO(2-1) line for our target, this configuration achieves the synthesized beam size of $0.''15 \times 0.''13$ in the natural-weighted map. Because our goal is detecting the diffuse emission extended over ∼10 kpc scale ($\sim 2''$ at $z = 6$), there is another option to choose the 94 core stations alone to target such diffuse emission. However, the resulting synthesized beam size with the core stations alone is too large (∼ 3" at 30 GHz) to distinguish the emission from the central galaxy and the halo area at $z = 6$. Based on several outputs from test runs, we fix the on-source

[1] https://ngvla.nrao.edu/page/tools

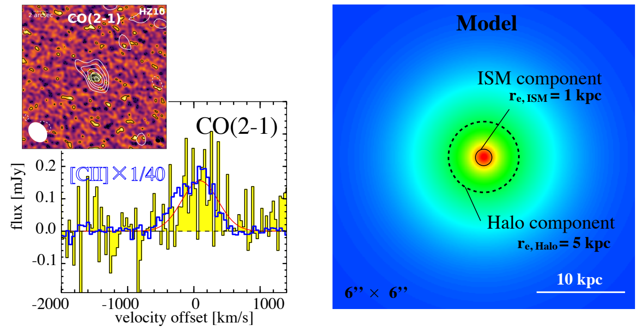

Fig. 2. Left: CO(2-1) line detection from Hz10 at $z = 5.65$ (Pavesi et al. 2019). The CO(2-1) spectrum (yellow) is shown with the normalized [C II] spectrum (blue). The white contour in the inset panel shows the velocity-integrated CO(2-1) intensity, where the background is that of the [C II] line. **Right**: Illustration of our model for the spatial distribution of the CO(2-1) line composed of the central ($r_\mathrm{e,cent} = 1$ kpc) and the halo component ($r_\mathrm{e,halo} = 5$ kpc).

integration time of 4 hours in our mock observations. To reduce the output visibility data size in the routine of the mock observations, we make the line channels averaged over as one continuum channel. For the output visibility data, we conduct TCLEAN with CASA down to the 2σ levels with the automask mode and standard TCLEAN parameters[2]. In addition to the natural weighting, we also produce lower resolution maps to recover the diffuse emission by applying several uv-taper parameters in the imaging process.

3. Results

In Figure 3, we summarize the CO(2-1) intensity maps averaged over the line width obtained by the mock observations. The top and bottom panels present the surface brightness profiles composed of ISM and ISM+Halo components, respectively. From left to right, we show the high to low-resolution maps by applying different uv-taper parameters. We identify the Halo component, i.e., the existence of the extended CO(2-1) structure (bottom panels) that is distinct from the morphology only with the ISM component (top panels) especially in the uv-tapered maps. The spatial resolution of the original map without uv-taper is likely too high to clearly identify the extended structure.

To quantitatively evaluate the identification of the Halo component, we also derive the radial profiles of the CO(2-1) line. In Figure 4, we summarize the radial profile with the beam profile for each map. We find that all of the maps show the extended structure in the ISM+Halo profile, where the structure is sufficiently recovered up to the radius of ∼15 kpc scale beyond the errors in the uv-tapered maps with the spatial resolution $> 0.''6$. We thus conclude that we can detect the CGM scale CO halo even from the star-forming galaxy at $z \sim 6$ with ngVLA, although the proper uv-taper is required.

[2] https://casaguides.nrao.edu/index.php/Automasking_Guide

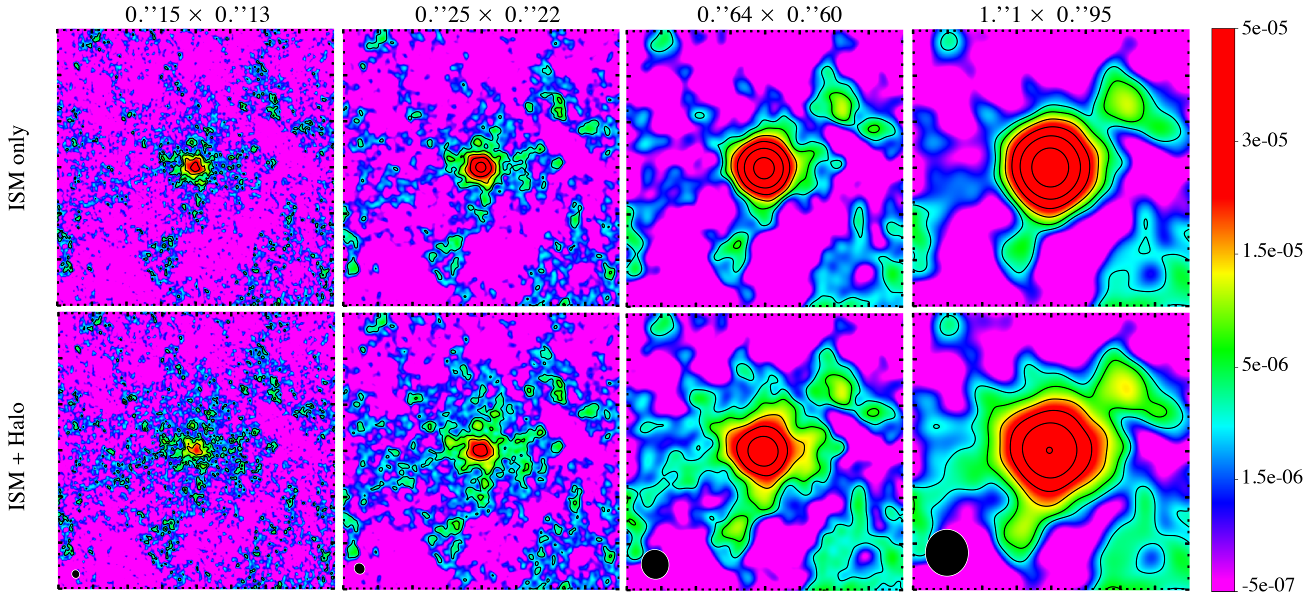

Fig. 3. Mock CO(2-1) observation maps ($6'' \times 6''$) with ngVLA for Hz10 at $z = 5.65$ by integrating 4 hours on source with the plain+core configuration. Top and bottom panels show the surface brightness profiles composed of the ISM component only and the ISM+Halo components (Figure 2), respectively. The natural weighted maps are shown from left to right without uv-taper, with uv-taper of $0.''1 \times 0.''1$, $0.''3 \times 0.''3$, and $0.''5 \times 0.''5$, respectively. The black contour starts at 3.5 μJy/beam and increases by a factor of 2. The black ellipse denotes the synthesized beam whose FWHM is presented at the top of the panel.

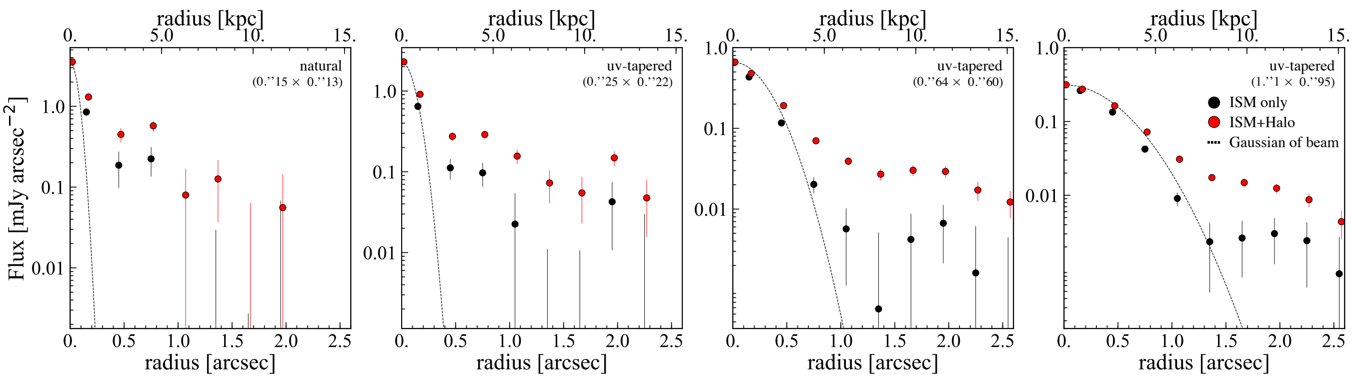

Fig. 4. Radial surface brightness profiles of the CO(2-1) line from the mock observations with ngVLA. The black and red circles indicate the radial profiles composed of the ISM component only and the ISM+Halo components (Figure 2), respectively. From left to right, the panels are arranged in the same order as Figure 3. The dashed curve denotes the Gaussian profile of the synthesized beam.

4. Discussion

4.1. [C II] with ALMA vs. CO(2-1) with ngVLA

Our mock observation results indicate that ngVLA requires more or less 4 hours on-source integration time to detect the CO(2-1) halo from Hz10-like object with SFR $\sim$130 $M_{\odot}$ yr^{-1}. This indicates that the required on-source integration time can exceed > 10 hours when we target less luminous objects and/or explore more time-expensive observations such as studying the kinematic of the halo. Although the low-J CO line is nevertheless essential to have a reliable mass estimate for the molecular gas extended over the CGM scale, it is also helpful to understand which is more time-efficient: targeting CO(2-1) with ngVLA or other bright FIR lines (e.g., [C II] 158 μm) with ALMA.

To address which observation is more time-efficient, we also perform mock observations with ALMA, targeting the [C II] halo with the same simulation setup. We use the same target of Hz10 whose [C II] line is also detected in previous studies (Capak et al. 2015). We model the same surface brightness profile and adopt the configuration C43-3 which has the synthesized beam size of $0.''68 \times 0.''64$ at the observed [C II] frequency in the natural weighting, almost comparable to one of the uv-tapered maps of ngVLA.

In Figure 5, we show the mock observation results with ALMA. We find that 1.5-hours on-source integration observations recover the [C II] halo structure up to the radius of $\sim$10 kpc, where the data quality is comparable to the mock observations with ngVLA. The absence of the emission from the radius of $\sim$10–15 kpc scale is likely because the less sampling in the short-baseline with ALMA, compared with the core station of ngVLA. These results ensure the power of ngVLA, allowing us to detect the faint low-J CO emission in the moderate integration time that does not exceed the required integration time with ALMA for the [C II] line more than a factor of several. However, it is also important to keep in mind that the observations for the bright FIR lines such as [C II] with ALMA could be more time efficient for CGM-scale gas studies around star-forming galaxies at $z \sim 6$ even in the era of ngVLA, if the objective of the study does not necessarily rely on the low-J CO line (e.g., the kinematics of the CGM).

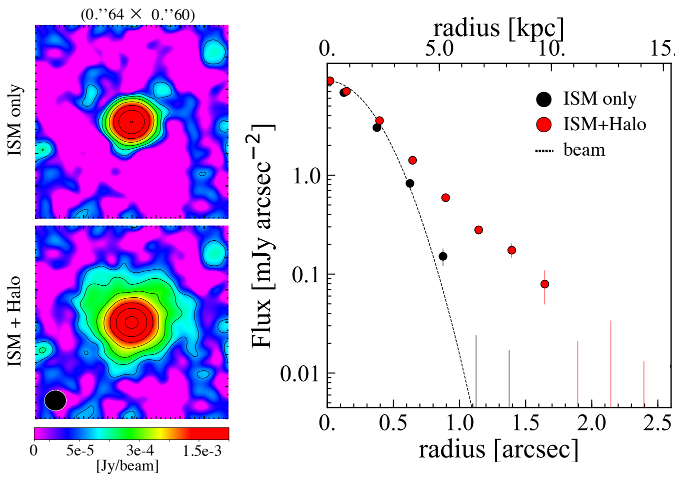

Fig. 5. Mock [C II] observation maps ($6'' \times 6''$) with ALMA for Hz10 at $z = 5.65$ composed of the the ISM component only (left top) and the ISM+Halo components (left bottom) by integrating 1.5 hours on source with the C43-3 configuration. In the right panel, the symbols are assigned in the same manner as Figure 4.

4.2. *Before the era of ngVLA*

Studying the low-J CO line for high-redshift star-forming galaxies will be one of the main streams in the era of ngVLA (e.g., Decarli et al. 2018; Casey et al. 2018; Carilli & Shao 2018; Emonts et al. 2018). In this context, it is important to enlarge the sample with the low-J CO line detection at least from the ISM component and understanding the basic low-J CO line properties and its realistic feasibility to further explore CGM-scale low-J CO studies in the era of ngVLA.

So far, the CO(2-1) line has been detected only from Hz10 with the deep VLA observations, and none of the CO(1-0) lines has been detected among star-forming galaxies at $z > 5$, except for the dusty starburst population (SFR $\gtrsim$ 500 $M_\odot$ yr^{-1}; e.g., Riechers et al. 2013). The recent deep and wide optical survey with Subaru Hyper Sprime-Cam (HSC) has been identified $>$ 10,000 of Lyman-break galaxies (LBGs) at $z \sim$ 5–7 (Ono et al. 2018) that are comparably bright as Hz10, and follow-up observations successfully detect bright FIR lines of [C II] and [O III] (Harikane et al. 2020). These bright HSC LBGs would be prominent targets to dramatically enlarge the sample size of the CO(2-1) and CO(1-0) line detection and investigate the feasibility of the low-J CO lines among the star-forming galaxies at $z > 5$.

We caution that the results obtained from these bright objects might be biased. In fact, the rest-frame ultra-violet (UV) luminosity of Hz10 is ~ 5 times larger than the characteristic UV luminosity at $z = 6$ ($M^*_{\rm UV} = -20.91$; Ono et al. 2018). To reduce the bias, another solution is the strongly lensed objects. Fujimoto et al. 2021 report the uniquely bright [C II] line detection from a strongly lensed and multiply imaged sub-L^* galaxy at $z = 6.072$ with SFR $\sim 5\ M_\odot$ yr^{-1} and $M_{\rm star} \sim 1 \times 10^9\ M_\odot$. Owing to the strong gravitational lens effect, the observed UV and [C II] line luminosities are the brightest ($m_{\rm UV} = 23.7$ mag$_{\rm AB}$, $L_{\rm [CII]} = 4.5 \times 10^9\ L_\odot$) among the star-forming galaxies at $z > 6$ known to date. Khullar et al. 2021 also report the identification of a remarkably bright ($m_{\rm UV} = 20.47$ mag$_{\rm AB}$) lensed galaxy at $z = 5.04$. These bright properties of strongly lensed galaxies will allow us to explore unprecedented faint lines, including the low-J CO lines, even before the era of ngVLA with the less biased view.

An important notice is that the diffuse emission is suffered from the cosmic microwave background (CMB) at such high redshifts like $z > 5$ (e.g., da Cunha et al. 2013; Zhang et al. 2016), but it depends on the ISM properties, including the gas density and kinematic temperature that could be constrained via Large velocity gradient (LVG) modeling for the CO spectral line energy distribution (e.g., Weiss et al. 2007). With the current facilities, the multiple CO lines from low to high-J can be obtained with the combination of e.g., VLA and ALMA for star-forming galaxies at $z \sim 6$. The bright LBGs and strongly lensed galaxies at $z > 5$ will also be helpful to constrain these ISM parameters to understand how significantly the CMB affects the emissivity of the low-J CO line before the era of ngVLA.

5. Summary

In this memo, we study the ability of ngVLA to detect the low-J CO halo around star-forming galaxies at $z \sim 6$ via realistic mock observations. Based on the mock observation results, we also discuss the time efficiency compared to the [C II] observations with ALMA and what we should do before the era of ngVLA. The major findings are summarized below:

1. The CGM (radius $\sim$ 10–15 kpc) scale CO(2-1) halo is clearly recovered and distinguished from the ISM-scale emission in the proper uv-tapered maps obtained with the plain+core configuration and 4 hours on-source integration, when we assume the CO(2-1) line properties of Hz10 with SFR $\sim 130\ M_\odot$ yr^{-1} at $z = 5.65$.
2. When we assume the CO(2-1) and [C II] line properties of Hz10, we find that the [C II] line observations with ALMA is more time efficient to detect the emission from the halo by a factor of $\sim$2–3.
3. To maximize outcomes in the era of ngVLA based on an enlarged sample with the low-J CO line detection among star-forming galaxies at $z > 5$, it is promising to carry out deep CO observations towards bright HSC LBGs (e.g., Ono et al. 2018; Harikane et al. 2020) and strongly lensed galaxies (e.g., Fujimoto et al. 2021; Khullar et al. 2021) at $z > 5$ with the current facilities such as VLA and ALMA, before the era of ngVLA.

6. Acknowledgements

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