Early Disk-Galaxy Formation from JWST to the Milky Way
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JWST observations of ALMA [O III] 88 μm emitters in the epoch of reionization

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Abstract. Understanding properties of galaxies in the epoch of reionization (EoR) is a frontier in the modern astronomy. ALMA observations have demonstrated that i) some [O III] 88 μm emitters have matured stellar populations at $z > 6$, implying early star formation activity at $z > 10$, and that ii) high-z star-forming galaxies typically have very high [O III] 88 μm-to-[C II] 158 μm luminosity ratios ranging from 3 to 12 or higher, indicating interstellar media of high-z galaxies could be highly ionized. We discuss initial results of a medium-sized JWST GO1 program that targets a sample of 12 $z = 6 - 8$ ALMA [O III] 88 μm emitters with NIRCam and NIRSPec IFU modes (GO-1840). Our JWST GO1 program, in conjunction with ALMA data, will characterize the stellar, nebular, and dust properties of these [O III] 88 μm emitters and place this galaxies in the context of reionization.

Keywords. galaxies: high-redshift, galaxies: ISM, galaxies: star formation.

1. Introduction

Understanding properties of galaxies at redshift of $z \gtrsim 6$ is crucial to study galaxy formation and evolution as well as the process of cosmic reioinization. With the advent of the James Webb Space Telescope *(JWST)*, it has become possible not only identifying ditantant galaxies well before the completion of reionization, but also studying their detailed properties such as their stellar populations and chemical enrichment by probing rest-frame ultraviolet to optical emission (e.g., Curtis-Lake et al. 2022). ALMA has a unique capability to study rest-frame far-infrared properties of high-z galaxies such as the far-infrared fine structure lines of [C II] 158 μm and [O III] 88 μm, and dust thermal continuum emission.

With ALMA, Hashimoto et al. (2018) have identified a galaxy behind a strong lensing cluster MACS1149, MACS1149-JD1, at $z = 9.1$ with [O III] 88 μm. Interestingly, MACS1149-JD1 shows a prominent Spitzer/IRAC color excess in the channel at 4.5 μm, as shown in Figure 1. As the spectroscopic redshift was determined to be at $z = 9.1$, the authors have concluded that the color excess cannot be due to the contamination by strong optical emission lines such as Hβ and [O III] 4959, 5007 Å, because these emission lines are redshifted outside of the coverage of the IRAC 4.5 μm channel. Instead Hashimoto et al. (2018) have demonstrated that the color excess is due to the Balmer break, indicating that the galaxy at $z = 9.1$ already has a matured stellar population. Based on the detailed spectral energy distribution (SED) fitting to the rest-frame ultraviolet to far-infrared data, the authors have shown that the formation epoch of MACS1149-JD1 is as early as $z \sim 15$, which is actually consistent with the recent spectroscopic identifications of $z \sim 13$ galaxies with *JWST* (Curtis-Lake et al. 2022).

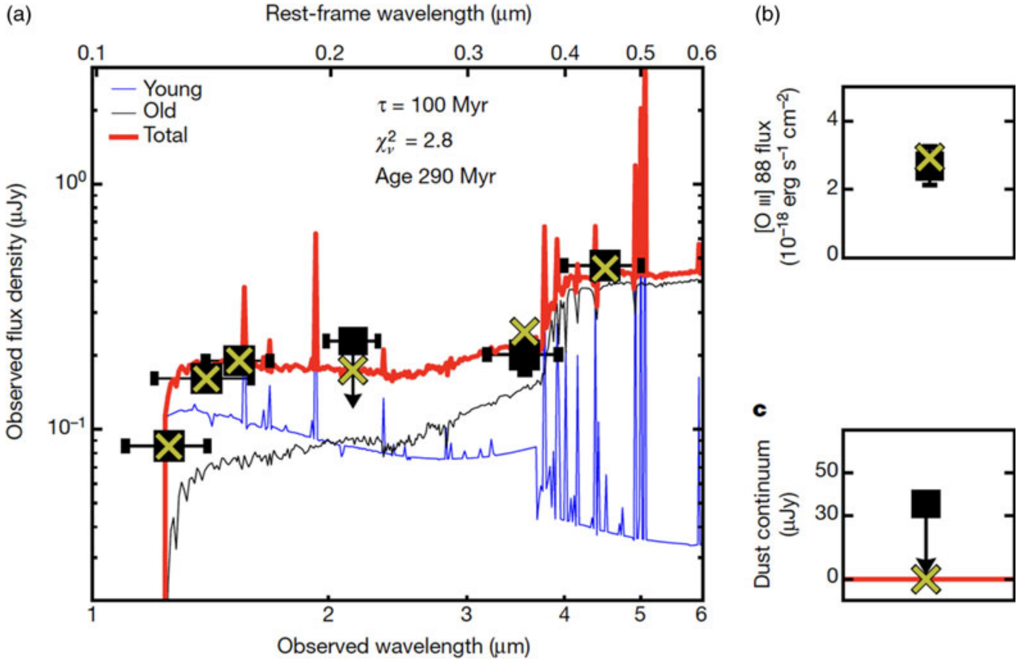

Figure 1. SED of MACS1149-JD1 at $z = 9.11$. In the left panel, the black squares indicate the photometry obtained from HST, VLT, and Spizer, whereas the horizontal error bars indicate the wavelength coverages of each broad band filiter. The red, blue, and black solid lines show the model SED of the total, young, and old stellar populations, respectively, whereas the yellow crosses show the modelled flux densities convolved with each broad band filter. The top right and bottom right panels show the [O III] 88 μm and dust continuum information, where the meanings of the symbols are the same as those in the left panel. The figure is quoted from Hashimoto et al. (2018).

However, it remains unclear what physical processes have ceased the star formation activity in MACS1149-JD1. Indeed, theoretical works of Binggeli et al. (2019) had difficulty in reproducing the Balmer break as strong as observed in the galaxy in e.g., FIRE-2 simulations, implying that some simulations may miss key ingredients for the quenching process (e.g., feedback) or that ALMA [O III] 88 μm emitters such as MACS1149-JD1 constitute a rare population of high-z galaxies. Alternatively, Katz et al. (2019) have successfully reproduced the observed Balmer break if dust preferentially exists in the vicinity of young massive stars. In any case, the presence of older stellar populations in MACS1149-JD1 motivates us to systematically examine the prevalence of older stellar populations among the high-z galaxies. This usually requires deep photometric data in conjunction with spectroscopic data that allows one to remove the contamination from strong optical emission lines to the photometry.

Another interesting feature of high-z ALMA galaxies is their high [O III] 88 μm-to-[C II] 158 μm luminosity ratios. Hashimoto et al. (2019) have compiled the observations of high-z galaxies observed in the two emission lines, and showed that the high-z galaxies have the luminosity ratios ranging from 3 to 20. The high luminosity ratios have been later confirmed by e.g., Harikane et al. (2020) with a larger sample. The luminosity ratio of ~ 3 is similar to those in typical dwarf galaxies in the local universe, whereas the luminosity ratio > 10 has rarely been observed in the local universe. Harikane et al. (2020) have performed detailed CLOUDY modelling to examine physical origins of the the high luminosity ratios among the high-z galaxies, as shown in Figure 2. Although

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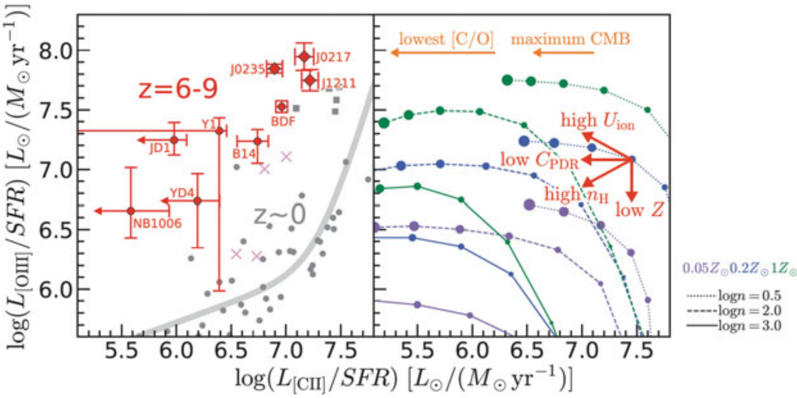

Figure 2. The [O III] and [C II] line luminosities divided by star formation rates. In the left panel, red and grey data points indicate high-z and local galaxies, respectively. The right panel shows the calculations of the photo-ionization modes, CLOUDY, that take into account both the H II regions and the photo-dissociated regions. The figure is quoted from Harikane et al. (2020).

there are a number of scenarios for the high luminosity ratios, e.g., low [C/O] abundance ratio, high gas density, low gas-phase metallicity, the both authors have shown that the high luminosity ratios could imply the high ionization state or low-neutral gas covering fraction of the interstellar medium (ISM), which facilitate the escape of Lyman continuum photons ($\lambda \geq 912$ Å) from galaxies into the surrounding intergalactic medium without being absorbed by neutral hydrogen atoms in the ISM. If this is the case, the ALMA [O III] 88 μm emitters could have significantly contributed to the reionization process. However, due to the degeneracies among the parameters, ALMA data alone were not able to decisively conclude their ISM properties.

2. Overview of the *JWST* GO-1840 program

To address these questions raised by ALAM observations of high-z galaxies, as part of the Reionization and the ISM/Stellar Origins with JWST and ALMA (RIOJA) project, we are conducting follow-up observations of twelve [O III] 88 μm emission line galaxies at $z = 6.0 - 8.3$ identified by ALMA with NIRCam and NIRSpec IFU onboard JWST (GO-1840, PIs: J. Álvarez-Márquez and T. Hashimoto). The sample selection was based on a complete sample of fourteen ALMA [O III] 88 μm emitters at $z = 6.0 - 9.1$, two of which (MACS1149-JD1 and MACS0416-Y1) were removed because they were included in several GTO programs. The targeted galaxies have a high dynamic range in the ultraviolet absolute magnitudes ranging from -23 to -20, which covers the typical to bright-end Lyman break galaxies.

The NIRCam observations use six filters carefully selected for the targeted galaxies on the individual basis. The shorter three wave bands probe the rest-frame ultraviolet continuum that traces the young massive stars. The two longer wave bands probe the wavelengths around the Balmer break, and the longest wave band probes the rest-frame optical continuum contaminated by strong optical emission lines such as [O III] 5007 Å and Hα. The NIRSpec IFU observations adopt a grating/filter pair of G395H/F290LP (F395MF290LP) that produces a cube with a spectral resolution of $R \sim 2700$ ($R \sim 1000$) in a wavelength range of 2.87-5.27 μm for the galaxies at $z \sim 6.0 - 6.8$ and 7.9 ($z \sim 7.1$). The NIRSpec IFU data provide strong optical emission lines such as [O II] 3727, 3729 Å, Hβ, [O III] 4959, 5007 Å, and Hα.

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Combination of the NIRCam and NIRSpec IFU data is crucial to accurately measure the optical line fluxes that contaminate the NIRCam images, thereby performing accurate SED fitting of the targeted galaxies. With these data, we plan to examine the stellar buildup of the targeted galaxies, how the older stellar populations are prevalent among the high-z [O III] 88 μm emitters. Because all the targeted galaxies have information on dust from ALMA regardless it is detected or not, we can examine spatial distributions of stars, ionized gas, and dust in these galaxies. With these spatial information, we plan to examine whether these early galaxies have formed as compact clumps or in a large extended gaseous disks. These two will address our first question: the prevalence of older stellar populations in the early galaxies. With the NIRSpec IFU data, we plan to obtain important ISM parameters such as the ionization parameter, gas-phase metallicity, electron density, and electron temperature. In this respect, the combination of ALMA [O III] 88 μm and *JWST* optical [O III] 4959, 5007 Å emission lines has potential to constrain the electron temperature even without the fainter [O III] auroral line at 4363 Å (Nakazato et al. 2023), which is crucial to estimate the gas-phase metallicity accurately. These ISM parameters will allow us to understand the second question: physical origins of the high ALMA [O III]88 μm-to-[C II]158 μm luminosity ratios, how the galaxy population has contributed to the reionization process.

3. Initial results of the *JWST* GO-1840 program and summary

Here we describe two initial results obtained in the GO-1840 program. Because these results are ongoing and before the publication, we opt not to show figures in public.

An interesting candidate proto-cluster, A2744-z7p9O, at $z \approx 7-8$ behind the strong lensing cluster Abell 2744 was reported by independent groups (e.g., Laporte et al. 2014) based on photometric redshift deduced from *HST* data taken as a part of Hubble Frontier Fields Survey (PI: Lotz) in conjunction with *Spitzer*/IRAC data. Remarkably, the proto-cluster candidate includes as many as eleven (eleven) member galaxy candidates at $7 < z < 8$ ($8 < z < 9$) within just a single field of view of *HST* WFC3. Among these, particularly interesting is the presence of "quintet" galaxy candidates at $z \sim 8$ named A2744-YD1, YD4, YD6, YD7, and zD1 in an apparent distance of just $\sim 30 \times 30$. Recently, Morishita et al. (2022) have reported the spectroscopic redshift of A2744-z7p9O by identifying seven galaxies at $z = 7.88$ with [O III] 5007 Å. The observations were made by JWST ERS and DDT programs using the micro shutter array (MSA) mode with a prism ($R \sim 100$) and/or medium-resolution ($R \sim 1000$) configurations.

In our GO1 program, we targeted the "quintent" galaxy candidates with NIRSpec IFU with a high spectral resolution mode. Among the five member galaxy candidates, A2744-YD1, YD4, YD6, YD7, zD1, we clearly detected three member galaxies, A2744-YD1, YD4, YD7, and one additional serendipitous galaxy, A2744-S1, at $z \sim 7.88$ within a single field-of-view of IFU. A2744-S1 was not recognized as a $z \sim 8$ candidate in the previous literatures based on the HST and Spitzer data. This clearly demonstrates the power of IFU observations to understand the true structure of a proto-cluster in a less biased manner. The A2744-zD1 galaxy was not identified in our spectra, likely due to its fainter nature. In the four identified galaxies, we obtained the optical [O III]-to-[O II] luminosity ratio ranging from 4 to 9, suggesting that the ISM of these galaxies are highly ionized, whereas they show a wide variety.

We have presented the previous ALMA observations of high-z galaxies and their puzzles, and our ongoing *JWST* GO1 program that will address these questions. With the combined data set of ALMA and *JWST* NIRCam and NIRSpec IFU, our data will serve as a reference case for future spatially-resolved properties of high-z galaxies.

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