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Detections of far-infrared [OIII] and dust emission in a galaxy at $z = 8.312$: Early metal enrichment in the heart of the reionization era

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Abstract. We present ALMA detection of the [O III] 88 μm line and 850 μm dust continuum emission in a Y-dropout Lyman break galaxy, MACS0416_Y1. The [O III] detection confirms the object with a spectroscopic redshift to be $z = 8.3118 \pm 0.0003$. The 850 μm continuum intensity (0.14 mJy) implies a large dust mass on the order of $4 \times 10^6 M_\odot$. The ultraviolet-to-far infrared spectral energy distribution modeling, where the [O III] emissivity model is incorporated, suggests the presence of a young ($\tau_{\rm age} \approx 4$ Myr), star-forming (SFR $\approx 60\ M_\odot$ yr^{-1}), and moderately metal-polluted ($Z \approx 0.2 Z_\odot$) stellar component with a stellar mass of $3 \times 10^8 M_\odot$. An analytic dust mass evolution model with a single episode of star formation does not reproduce the metallicity and dust mass in ≈ 4 Myr, suggesting an underlying evolved stellar component as the origin of the dust mass.

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

1. Introduction

How and when metal enrichment happened in the epoch of reionization (EoR) is one of the most fundamental questions in modern astronomy. Recent *Planck* results suggest an instantaneous reionization redshift of $z_{\rm re} = 7.68 \pm 0.79$ Planck Collaboration (2018), and the latest *Hubble Space Telescope* (*HST*) surveys have revealed more than a hundred of candidate $z \gtrsim 8$ Lyman break galaxies (LBGs). Furthermore, based on the samples of $z \gtrsim 8$ LBGs, Oesch *et al.* (2018) reported strong evolution of the ultraviolet (UV) luminosity function from $z \sim 10$ to $\sim$8, implying a rapid increase of the cosmic star-formation rate density by an order of magnitude within a very short time-scale ($\lesssim 200$ Myr). Hence, characterizing star formation and interstellar medium (ISM) of galaxies at the pre-reionization era ($z \gtrsim 8$) is an important next step to our understanding of the earliest evolution of galaxies.

Inoue *et al.* (2014) predicted that the [O III] 88 μm line, which is often observed as the brightest far-infrared (FIR) line in local H II regions, is detectable with ALMA and can be used as an instantaneous tracer of massive star formation at $z \sim 8$. Since our first ALMA detection of the [O III] line in a $z = 7.212$ Lyα emitter, SXDF-NB1006-2 (Inoue *et al.* 2016), there have been mounting detections of the [O III] line in the EoR (e.g., Hashimoto *et al.* 2018; Sunaga *et al.* 2018). Furthermore, the [O III] line plays an important role in characterizing physical properties of $z \gtrsim 8$ galaxies because it is extinction-free and sensitive to SFR, stellar age, and gas-phase oxygen abundance.

In this paper, we report ALMA detections of [O III] and dust emission in a Y-dropout galaxy MACS0416_Y1 (Tamura *et al.* 2018), which is a robust candidate for a $z \sim 8$ LBG found behind the Frontier Field cluster, MACS J0416.1−2403 (Laporte *et al.* 2015).

2. ALMA Observations and Results

In our ALMA Cycle 4 observations of MACS0416_Y1, four different tunings were assigned to cover a frequency range between 340.0 and 366.4 GHz. The total on-source time was 7.3 hr. The data sets are combined to make the continuum image and a spectral cube with a frequency resolution of 31.25 MHz (≈ 26 km s^{-1}) to search for the [O III] line.

We detect 850-μm continuum emission at the position of MACS0416_Y1 as shown in Fig. 1a. The emission is spatially resolved ($\approx 0\farcs3 \times 0\farcs1$) and is similar in spatial distribution on a $\sim$1 kpc scale to that of the rest-frame UV emission. The bulk of dust emission is likely to be associated with the eastern 'E' knot, **while the 'C' and 'W' knots also have the dust emission** (Fig. 1c). The observed flux density of $S_{850\,\mu{\rm m}} = 137 \pm 26\ \mu$Jy corresponds to a de-lensed total IR luminosity of $L_{\rm IR} = (1.7 \pm 0.3) \times 10^{11} L_\odot$ and a dust mass of $M_{\rm dust} = (3.6 \pm 0.7) \times 10^6 M_\odot$ if assuming a dust temperature of $T_{\rm dust} = 50$ K, a dust emissivity index of $\beta = 1.5$, a dust emissivity of $\kappa_{\rm d}(850\ \mu{\rm m}) = 0.15$ m^2 kg^{-1} and the magnification factor of $\mu_{\rm g} = 1.43 \pm 0.04$.

At the position of the dust emission, we detect an emission line feature at 364.377 ± 0.012 GHz, strongly suggesting the [O III] 88 μm emission line at $z = 8.3118 \pm 0.0003$ (Fig. 1b). The apparent line flux is $F_{\rm [O\,III]} = 0.66 \pm 0.16$ Jy km s^{-1}, corresponding to the delensed line luminosity of $L_{\rm [O\,III]} = (1.2 \pm 0.3) \times 10^9 L_\odot$.

3. UV-to-FIR SED Modeling

This dust continuum detection is somewhat surprising because the UV slope is blue ($\beta_{\rm UV} \approx -2$, **where $\beta_{\rm UV}$ is defined as a power-law index of the UV flux density $F_\lambda \propto \lambda^{\beta_{\rm UV}}$**). Furthermore, the *Spitzer*/IRAC photometry shows a red color in the rest-frame optical ([3.6]−[4.5] > 0.38). These spectral features are similar to those found in lower-z low mass star-forming galaxies, while the full SED should be assessed for the better understanding of the physical property of MACS0416_Y1.

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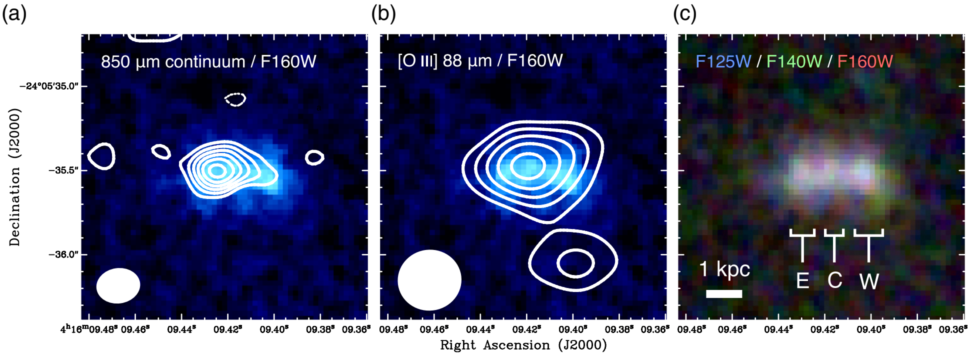

Figure 1. (a) The ALMA 850 μm continuum image of MACS0416_Y1 (contours) overlaid on the *HST*/WFC3 near-infrared image in the F160W band. The contours are drawn at -2σ, 2σ, $3\sigma, \ldots, 7\sigma$, where $\sigma = 10.9$ μJy beam^{-1}. The synthesized beam size is indicated at the bottom-left corner. (b) The ALMA [O III] 88 μm integrated intensity image (contours) overlaid on the *HST*/F160W image. The contours are drawn in the same manner as (a), but $\sigma = 55$ mJy beam^{-1} km s^{-1}. The image is optimally tapered with a $0\farcs35$ Gaussian kernel to maximize the signal-to-noise ratio. (c) The *HST*/WFC3 image taken with F160W (red), F140W (green) and F125W (blue) bands. The letters 'E', 'C' and 'W' denote the positions of the eastern, central, and western clumps seen in the rest-frame UV, respectively. The physical scale of 1 kpc on the image plane is indicated by the bar at the bottom-left corner.

We characterize the SED to investigate the physical properties of MACS0416_Y1 by template fits. The model is based on the prescription presented by Mawatari *et al.* (2018)†, where the emission components of a stellar continuum (Bruzual & Charlot 2003), the rest-frame UV-to-optical nebular lines and continuum (Inoue 2011), and the dust continuum (Rieke *et al.* 2009) are accounted for, **with the assumption that the absorbed UV-to-optical emission is reprocessed as the FIR emission.** In addition, we take into account the [O III] 88 μm emissivity model (Inoue *et al.* 2014). We use the photometric data of the 850 μm continuum and [O III] line in addition to the rest-frame UV-to-optical bands to model the SED of MACS0416_Y1.

The results are shown in Fig. 2. One of the important outcomes is that there exist solutions which reasonably explain the large amount of dust coexisting with the young stellar components. Regardless of standard extinction laws, the SED fits favor a young, high-SFR solution, where large equivalent widths of the enhanced [O III] $\lambda\lambda$4959, 5007 Å and Hβ lines contribute to the [3.6]$-$[4.5] color. The SFR and age are estimated to be ≈ 60 $M_\odot$ yr^{-1} and ≈ 4 Myr, respectively, suggesting that MACS0416_Y1 is at the onset of a starburst phase. The stellar mass visible in the UV-to-optical is estimated to be $M_{\rm star} \approx 3 \times 10^8 M_\odot$. The best-fitting metallicity already reaches $Z \approx 0.2 Z_\odot$ at $z = 8.3$ despite a large uncertainty, suggesting rapid enrichment of heavy elements in the middle of the reionization era.

4. Evolved Stellar Component as the Origin of Dust

The SED analysis does not, however, explain how the galaxy has *obtained* the large amount of dust, even though **the SED model treats the energy balance self-consistently** if assuming that the dust *preexists*. The inferred dust-to-stellar mass ratio ($\sim 10^{-2}$) is two orders of magnitude higher than those found in dusty star-forming galaxies, suggesting the presence of a passively-evolved stellar component which does not

† Panchromatic Analysis for Nature of HIgh-z galaxies Tool (PANHIT), which is available for download at http://www.icrr.u-tokyo.ac.jp/%7Emawatari/PANHIT/PANHIT.html.

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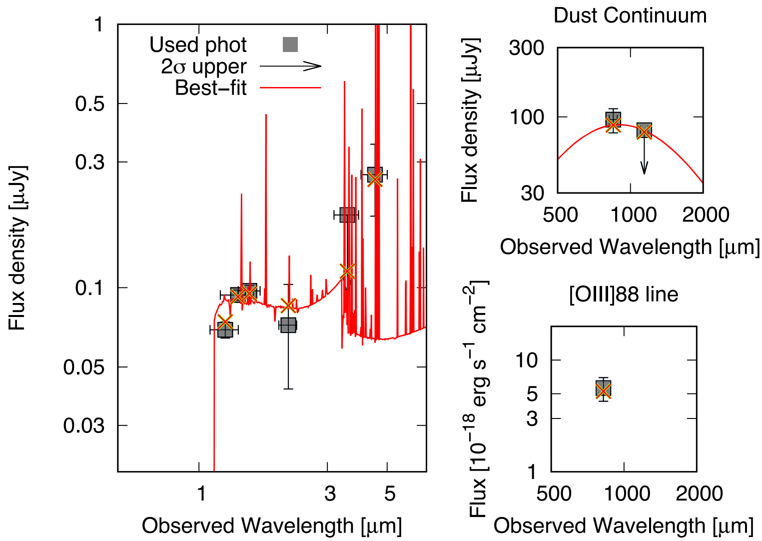

Figure 2. The best-fitting spectral energy distribution (SED, solid curve) obtained for the Calzetti *et al.* (2000) dust extinction law. The filled squares represent the observed photometric data points. The ALMA constraints are shown in the small panels. The crosses are flux densities (or flux for the [O III] 88 μm line) predicted from the model.

dominate the UV-to-optical light. Furthermore, a dust formation model (e.g., Asano *et al.* 2013) assuming a single episode of star formation does not reproduce the dust mass and metallicity in the galaxy age of ≈ 4 Myr. This strongly suggests that the ISM was already metal-polluted before the onset of the current episode of star formation.

Obviously, the disagreement should be mitigated if assuming the presence of an underlying evolved stellar component assembled in a past star-formation activity. We find not only that a 0.3 Gyr-old stellar component can reproduce the dust mass and metallicity, but also that the addition of the evolved stellar component does not substantially change the stellar SED. Therefore, it is likely that the mature (with an age of $\sim$0.3 Gyr) stellar population with no or little ongoing star formation may be the origin of the very early enrichment of metal and dust.

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Discussion

Tomo Goto: [O III] and 850 μm might have a spatial offset. If separated, both components might be on the local relation on the $L_{[\mathrm{OIII}]}/L_{\mathrm{TIR}}$ versus L_{TIR} plot?

Yoichi Tamura: Yes, I believe so. The current spatial resolution for [O III] is not enough to resolve the galaxy, but if we spatially resolve it — actually we are going to do so in the current cycle of ALMA — the three components might follow the local relation.

Fabio Fontanot: I am wondering if a top-heavy initial mass function can loosen the tensions you find in the dust content?

Yoichi Tamura: As you pointed out, thermally pulsating asymptotic giant branch stars will supply more dust, which is great, but I think more frequent supernovae will destroy dust grains, which might suppress the increase in dust mass. I could not tell which effect is more efficient, but we can test how the change in the initial mass function would affect the dust mass by modifying the dust model.

David Rosario: In low-mass galaxies with high specific star formation rates, simulations show a substantial loss of metal-enriched gas in feedback-driven outflows. If this also applies to MACS0416_Y1, how is the star formation history required to produce the altered dust? Is this effect included in the dust evolution models used?

Yoichi Tamura: I do not think I can answer to your question quantitatively since our dust evolution model is a "closed box". However, I would say qualitatively that it would be necessary to put a star formation activity with longer star formation histories and lower star formation rates into the model. In this case, the formation epoch dates back to $z \sim 15$ or even higher, but a long duration of star formation can trigger non-linear grain growth in the interstellar medium, which facilities reproducing the observed dust mass.

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