EMPERESS. VII. Ionizing Spectrum Shapes of Extremely Metal-poor Galaxies: Uncovering the Origins of Strong HeII and the Impact on Cosmic Reionization

Hiroya Umeda1,2, Masami Ouchi1,3,4, Kimihiko Nakajima3, Yuki Isobe1,2, Shohei Aoyama1, Yuichi Harikane1,5, Yoshiaki Ono1, and Akinori Matsumoto1,2

1 Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan; ume@icrr.u-tokyo.ac.jp
2 Department of Physics, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
3 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
4 Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Chiba 277-8583, Japan
5 Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

Abstract

Strong high-ionization lines such as He II of young galaxies are puzzling at high and low redshift. Although recent studies suggest the existence of nonthermal sources, whether their ionizing spectra can consistently explain multiple major emission lines remains a question. Here we derive the general shapes of the ionizing spectra for three local extremely metal-poor galaxies (EMPGs) that show strong He II λ4686. We parameterize the ionizing spectra composed of a blackbody and power-law radiation mimicking various stellar and nonthermal sources. We use photoionization models for nebulae and determine seven parameters of the ionizing spectra and nebulae by Markov Chain Monte Carlo methods, carefully avoiding systematics of abundance ratios. We obtain the general shapes of ionizing spectra explaining ~10 major emission lines within observational errors with smooth connections from observed X-ray and optical continua. We find that an ionizing spectrum of one EMPG has a blackbody-dominated shape, while the others have convex downward shapes at >13.6 eV, which indicate a diversity of the ionizing spectrum shapes. We confirm that the convex downward shapes are fundamentally different from ordinary stellar spectrum shapes, and that the spectrum shapes of these galaxies are generally explained by the combination of the stellar and ultraluminous X-ray sources. Comparisons with stellar synthesis models suggest that the diversity of the spectrum shapes arises from differences in the stellar age. If galaxies at z > 6 are similar to the EMPGs, high-energy (>54.4 eV) photons of the nonstellar sources negligibly contribute to cosmic reionization due to relatively weak radiation.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); Dwarf galaxies (416); Ultraluminous x-ray sources (2164)

1. Introduction

Understanding the epoch of reionization (EoR) is one of the most important goals for astronomy today. Many studies have suggested that galaxies are the dominant sources of ionizing photons at the EoR (e.g., Wise et al. 2014; Madau & Haardt 2015; Stanway et al. 2016). From hydrodynamical simulations, high-redshift young galaxies at the early formation phase are expected to have low metallicities, low stellar masses, and high specific star formation rates (e.g., Wise et al. 2012). High-redshift galaxies are studied with various large telescopes including the Hubble Space Telescope (e.g., Bouwens et al. 2015; Harikane et al. 2016; Livermore et al. 2017; Atek et al. 2018; Oesch et al. 2018; Kikuchihara et al. 2020). Although there are spectroscopic studies for very bright or lensed galaxies at high redshifts (e.g., Stark et al. 2015; Maina1 et al. 2018; Shibuya et al. 2018), dwarf galaxies at high redshift are too faint to be detected with current observational instruments. For example, even with the upcoming James Webb Space Telescope, we can detect Hα for galaxies with stellar masses below 10^8 M☉ only at z ≲ 2 without gravitational lensing (Isobe et al. 2022).

Owing to observational difficulties, many studies use local dwarf galaxies as analogs of high-redshift young dwarf galaxies (e.g., Berg et al. 2019). Among the local dwarf galaxies, local extremely metal-poor galaxies (EMPGs) are recently gaining attention (e.g., Izotov & Thuan 1998; Thuan & Izotov 2005; Sánchez Almeida et al. 2016; Kojima et al. 2020). EMPGs are defined as galaxies with metallicities below 10% of the solar metallicity Z☉. So far, EMPGs with metallicities down to 1.6% Z☉ have been identified using data obtained with the Subaru/Hyper Suprime Cam (HSC; Kojima et al. 2020). Local EMPGs have low masses and high specific star formation rates (sSFRs), both of which are comparable to those of high-redshift young galaxies (e.g., Wise et al. 2012). Local EMPGs are therefore regarded as local analogs of high-redshift young galaxies.

The importance of relationships between local EMPGs and high-redshift galaxies is further emphasized because very strong high-ionization nebular emission lines (i.e., He II, C III, C IV) are detected from local EMPGs (Guseva et al. 2000; Shirazi & Brinchmann 2012; Senchyna et al. 2017; Berg et al. 2019; Kojima et al. 2021) and high-redshift galaxies (Stark et al. 2015; Laporte et al. 2017; Schmidt et al. 2017; Maina1 et al. 2018). Most of the EMPGs have detections of optical recombination lines He II λ4686 that need high-energy ionizing photons (>54.4 eV; López-Sánchez & Esteban 2010; Shirazi & Brinchmann 2012; Senchyna et al. 2017). A statistical study of local galaxies shows that fluxes of He II λ4686 increase as the
metallicity decreases (e.g., Schaerer et al. 2019). These results indicate the presence of hard ionizing sources in metal-poor environments.

The origin of strong He II emission lines is still under debate. Xiao et al. (2018) examined contributions from stellar radiation using the photoionization code CLOUDY (Ferland et al. 2013) and the Binary Population and Spectral Synthesis (BPASS) code (Stanway et al. 2016; Eldridge et al. 2017). BPASS binary models incorporate contributions from hard radiation from Wolf–Rayet stars and stripped binary stars. However, a line ratio He II λ4686/Hβ predicted in Xiao et al. (2018) falls short of the observed value by more than 0.5 dex, suggesting that stars are not major contributors to the He II ionizing photons. Addition of extra stars (e.g., metal-poor, very massive, or Wolf–Rayet stars) could boost the He II ionizing photons, but several studies suggest that these stars cannot fully account for the observed strength of He II in EMPGs (e.g., Kehrig et al. 2018; Olivier et al. 2021). Pérez-Montero et al. (2020) suggest that ordinary stellar synthesis models with a nonzero ionizing photon escape fraction can explain He II λ4686/Hβ, but their models require very high escape fraction values (∼70%) that are not compatible with the typical values reported for z < 3 galaxies (e.g., Rutkowski et al. 2016; Steidel et al. 2018; Alavi et al. 2020; Izotov et al. 2021b; Schaerer et al. 2022).

Nonthermal ionizing sources have been proposed to explain the strong nebular He II from EMPGs. Active galactic nuclei (AGNs) are one of the candidates of nonthermal emission sources (e.g., Berg et al. 2018; Plat et al. 2019). Berg et al. (2018) found that AGN models can reproduce observed He II λ1640, while other emission lines, such as C IV λ1548,1551 and C III] λ1909, cannot be reproduced simultaneously. However, their AGN models do not consider metal-poor (z < 0.25 Z⊙) AGNs. Shocks are another candidate for the ionizing sources of He II (e.g., Thuan et al. 2005; Berg et al. 2018; Plat et al. 2019; Isobe et al. 2021). Berg et al. (2018) also examined contributions from radiative shocks using radiative shock models of Allen et al. (2008). Calculations with radiative shock models also suggest that radiative shocks cannot explain the strong He II λ1640 emission for a given intensity of other emission lines such as C IV λ1548,1551 and C III] λ1909 (see also Izotov et al. 2021a).

Alternatively, other hard radiation sources are also proposed. Schaerer et al. (2019) show that X-ray luminosities have a positive correlation with line ratios He II λ4686/Hβ with X-ray binary population models, indicating the contributions of the He II ionizing photons from high-mass X-ray binaries (HMXBs). Lebouteiller et al. (2017) demonstrated that HMXBs can be the sources of He II ionizing photons in well-studied EMPG I Zw 18 through detailed modeling of radiation fields and interstellar mediums. Kehrig et al. (2021) argue that the ultraluminous X-ray source (ULX) in I Zw 18 cannot fully account for all of He II ionizing photons. However, recent integral field spectroscopic observations of I Zw 18 suggest that the ULX still remains the possibility (see Rickards Vaught et al. 2021). Moreover, while Senchyna et al. (2020) argue that HMXBs cannot be the main contributors of He II in EMPGs through the photoionization models representing HXMB spectra by simple multicolor disk models, Simmonds et al. (2021) examined the photoionization models using several detailed spectrum models for HMXBs/ULXs and found that some of the models can reproduce He II λ4686/Hβ and other line ratios, such as [O III] λ4959,5007/Hβ and [O III] λλ4959,5007/[O II]λ3727. The studies of Schaerer et al. (2019), Simmonds et al. (2021), and Lebouteiller et al. (2017) claim that HMXB/ULX can explain strong He II emission lines (see Saxena et al. 2020 and Senchyna et al. 2020), but whether a simple physical model can explain all the emission lines from a galaxy in a self-consistent manner remains uncertain. There are also attempts to explain emission lines from EMPGs by the nonuniform interstellar medium (ISM; e.g., Ramambason et al. 2020; Berg et al. 2021; Izotov et al. 2021a). For example, Ramambason et al. (2020) showed that ordinary stellar population synthesis models can reproduce high-ionization emission lines [O III] λλ4959,5007 simultaneously with low-ionization emission lines [O II] λ3727 by introducing the so-called “two-zone” models.

Variations of models presented by these previous studies raise difficulties in reproducing strong He II emission line fluxes for given low-ionization line fluxes. Instead, we aim to determine the self-consistent general spectrum shape by a parametric method. By obtaining the general spectrum shapes first, we can infer the possibility of countless ionization sources without running costly calculations using photoionization code each time. Moreover, we expect to uncover the spectral features that were not previously mentioned.

In this work, we search for the self-consistent spectrum shapes that can reproduce observed emission line fluxes of three EMPGs. Similar work such as that by Olivier et al. (2021; hereafter, O21) uses blackbody and BPASS models to search for the spectrum shape. Another similar study uses combinations of BPASS models and ULX models as ionizing spectra (Simmonds et al. 2021). With the minimum assumptions, we construct generalized spectral models that cover spectrum shapes examined in O21 and Simmonds et al. (2021). We use a generalized spectrum as an ionizing spectrum in a uniform ISM to compute emission line fluxes using the photoionization code CLOUDY. We then search for the self-consistent spectrum shapes using the Markov Chain Monte Carlo (MCMC) method.

Our sample and methodology are described in Section 2. We present our results for the general spectrum shapes and reproduction of emission lines in Section 3. In Section 4, we evaluate several candidates for the hard radiation sources using the general spectrum shape. We also examine the contributions of the hard radiation sources to cosmic reionization. In Section 5, we summarize our main results. Throughout this paper, magnitudes are in the AB system, and we assume a standard Λ CDM cosmology with parameters of (Ωm, ΩΛ, H0) = (0.3, 0.7, 70 km s−1 Mpc−1) and the solar metallicity scale of Asplund et al. (2009), where 12 + log(O/H) = 8.69.

2. Sample and Methods

2.1. Sample

We investigate general ionizing spectrum shapes for a sample of three galaxies, J1631+4426, J104457, and I Zw 18 NW, whose properties are summarized in Table 1. All three galaxies are extremely metal-poor (Z < 0.001 Z⊙), nearby (z ~ 0), and low-mass (<107 M⊙) galaxies. J1631+4426 is the most metal-poor galaxy detected, with Z = 1.6% Z⊙ (Kojima et al. 2021; hereafter, K21). Thus, J1631+4426 is a good test-bed for investigating the nature of EMPGs. J104457 is a metal-poor galaxy, whose optical spectrum has been studied previously, and it has been shown that BPASS models alone cannot explain the high-energy ionization lines (Berg
et al. 2021; hereafter, B21). Olivier et al. (2021) have also studied J104457 and have shown that the combination of a blackbody and BPASS model can explain the multilevel emission lines of J104457. Therefore, we can compare our results to those of Olivier et al. (2021). I Zw 18 NW is one of the most well-known EMPGs that has optical and X-ray data (Thuan & Izotov 2005; hereafter, TI05). This allows us to check the consistency between the ionizing spectrum shapes beyond 54.4 eV and the X-ray luminosity data for I Zw 18 NW. All three galaxies in our sample have optical spectroscopic data available. In Figure 1, we present the locations of all three galaxies on a diagram of [N II]/Hα and [O III]/Hβ emission line ratios, the so-called the Baldwin–Phillips–Terlevich diagram (BPT diagram; Baldwin et al. 1981). The black dots represent the emission line ratios of z ~ 0 star-forming galaxies (SFGs) and AGNs from the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7). We note that Lebouteiller et al. 2004, Kojima et al. 2021, and Legrand et al. 1997 is a report of a Wolf–Rayet bump centered at 4645 Å for I Zw 18 NW, but no underlying broad component is detected for He II λ4686 (Legrand et al. 1997). Therefore, we treat He II λ4686 lines of our three galaxies as the nebular origin. All the line ratios in Table 2 use the dust-corrected fluxes.

2.2. Photoionization Models

We use the spectral synthetic code CLOUDY (version 17.02; Ferland et al. 2017) to calculate the emission line fluxes from a gas cloud ionized by a central ionizing source. With CLOUDY, we simulate physical conditions within a gas cloud to predict the emission line fluxes. To obtain the emission line fluxes, we use photoionization models with free parameters of ionizing spectra and nebulae. We describe these free parameters as well as the fixed parameters below.

2.2.1. Geometry and Density

In our photoionization model, we assume a spherical shell of the gas cloud surrounding the central ionizing source, in accordance with the default setting of CLOUDY.6 We fix the inner radius (outer radius) of the gas cloud R_in (R_out) at the default value. The default value of R_out is at R_out = 10^{20} cm, and this large R_out value produces an effectively plane-parallel

---

Table 1

| Name of the Galaxy | z | i (mag) | log(M_*) (M_☉) | log(SFR) (M_☉ yr⁻¹) | Z (Z☉) | F(H/β) (10⁻¹⁴ erg s⁻¹ cm⁻²) | EW(H/β) (Å) | L_X,0.5–10 keV (10³⁹ erg s⁻¹) | References |
|--------------------|---|---------|----------------|---------------------|--------|-----------------------------|-----------|-----------------------------|-----------|
| J1631 +4426        | 0.031 | 22.5 | 5.9 | -1.28 | 0.016 | 0.13 | 123.5 | ... | (a) |
| J104457            | 0.013 | 18.7 | 6.8 | -0.85 | 0.058 | 0.95 | ... | ... | (b), (c) |
| I Zw 18 NW         | 0.002 | 20.1 | 5.5 | -2.70 | 0.030 | 3.19 | 81.2 | 1.4–1.6 | (d), (e), (f), (g) |

Note. (1): Redshift; (2): i-band magnitude. The magnitudes are the cmodel magnitudes of Subaru/HSC (SDSS) for J1631 +4426 (J104457 and I Zw 18 NW); (3): Stellar mass; (4): Star formation rate (SFR). The SFR of I Zw 18 NW is derived from the Hα flux in the same manner as Isebe et al. (2021); (5): Gas-phase metallicity derived by the direct T_e method; (6): H/β flux; (7): Rest-frame equivalent width of an H/β emission line; (8): X-ray luminosity at 0.5–10.0 keV obtained by Chandra X-ray observations; (9): References for values in columns (1)–(8): (a) Kojima et al. (2020), (b) B21, (c) SDSS DR2 (Abazajian et al. 2004), (d) SDSS DR6 (Adelman-McCarthy et al. 2008), (e) TI05, (f) Lebouteiller et al. (2017), (g) Thuan et al. (2004).

---

Figure 1. Our three galaxies on the BPT diagram. The red, blue, and orange dots represent the emission line ratios of J1631 +4426, J104457, and I Zw 18 NW, respectively. The bars represent the errors of the emission line ratios. The red arrow indicates an upper limit with 1σ level for [N II]/Hα of J1631 +4426. The black dots represent z ~ 0 SFGs and AGNs derived from the emission line catalog of SDSS DR7. The solid curve depicts the maximum photoionization models that can be reproduced solely by stellar radiation (Kaufmann et al. 2003). The region left (right) to the solid curve is the SFG (AGN and composite) region.
Notes. Dust-corrected emission line fluxes and emission line ratios for all galaxies in our sample. The fluxes are all scaled with Hβ = 100, and taken from K21, B21, and TB05, except for [S II] 6316/6731 of J1631+4426. This line ratio of J1631+4426 is measured with the spectrum of Kojima et al. (2020) in the same manner as K21.

Table 2

| Ion         | Fluxes and Flux Ratios |
|-------------|----------------------|
|             | J1631+4426          |
|             | J104457             |
| I Zw 18 NW  | I Zw 18 NW          |
| Fγ/FHβ      | 0.14 ± 0.40         |
| [O II]λ3727,3729 | 2.11 ± 0.12         |
| He λ4026    | 2.17 ± 0.13         |
| Hα          | 2.32 ± 0.14         |
| [O III]λ4363 | 2.57 ± 0.16         |
| He λ4471    | 2.70 ± 0.17         |
| [O III]λ4959 | 2.94 ± 0.18         |
| [O III]λ5007 | 3.15 ± 0.19         |
| Hα          | 3.33 ± 0.26         |
| [O II]λ6364  | 3.55 ± 0.27         |
| [N II]λ6548  | 3.77 ± 0.28         |
| [Ne III]λ6583| 4.00 ± 0.30         |
| [O III]λ4959 | 4.22 ± 0.31         |
| He λ6678    | 4.45 ± 0.32         |
| Hα          | 4.68 ± 0.33         |
| [O III]λ5007 | 4.91 ± 0.34         |
| Hα          | 5.14 ± 0.36         |

2.2.2. Ionizing Spectra

Previous studies have examined ionizing spectra of blackbody, stellar, and hard radiation sources (e.g., ULXs), and combinations of these sources (e.g., Fernández et al. 2022; Olivier et al. 2021; Simmonds et al. 2021). However, for all the soft and hard radiation models, whether a single self-consistent model can explain the emission line fluxes from a single galaxy remains unclear. To solve this, we use a generalized ionizing spectrum composed of blackbody and power-law radiation. The flux of this spectrum at frequency ν is given as

\[ F_\nu = B(\nu, T_{BB}) + C_{mix} P(\nu, \alpha_X). \]

where

\[ B(\nu, T_{BB}) = \frac{h\nu^3}{\exp(h\nu/kT_{BB}) - 1}, \]

\[ P(\nu, \alpha_X) = \nu^{\alpha_X} \exp(h\nu/E_k) \exp(-h\nu/E_h), \]

where \( T_{BB}, C_{mix}, \alpha_X, h, \) and \( k \) are the blackbody temperature, the mixing parameter, the power-law index, the Planck constant, and the Boltzmann constant, respectively. For the power-law component, we define the lower (higher) cut energy \( E_k \) (\( E_h \)). We set \( E_k = 0.1 \) Ryd (\( E_h = 10.00 \) Ryd) to avoid strong free–free (pair-creation and Compton) heating. We limit the blackbody temperature and power-law index in the ranges of \( 4 \leq \log T_{BB} \leq 6 \) and \(-3 \leq \alpha_X \leq 1\), respectively. For \( C_{mix} \), we introduce the alternative parameter \( a_{mix} \) defined as

\[ a_{mix} = \frac{C_{mix}}{P(\nu = 1 \text{ Ryd}/h, \alpha_X)} = \frac{F_\nu(\nu = 1 \text{ Ryd}/h)}{F_\nu(\nu = T_{BB})}. \]

2.2.3. Chemical Abundance

We use the solar abundance ratios of Grevesse et al. (2010), i.e., GASS10 as an initial condition of our CLOUDY model calculations. We scale all the abundances linearly with the oxygen abundance. Dust-corrected emission line fluxes relative to the model Hβ are all scaled with Hβ = 100, and taken from K21, B21, and TB05, except for the solar abundance ratios of helium, carbon, and nitrogen. We assume that the extinction coefficients for dust correction will only have minor effects on our results.

2.2.4. Ionizing Spectrum Intensity

The intensity of the ionizing spectrum is specified with the ionization parameter \( U \). The ionization parameter is defined as

\[ U = \frac{Q(H^0)}{4\pi R_S^2 n_H c}, \]

where \( Q(H^0), R_S, \) and \( c \) are the intensity of ionizing photons above the Lyman limit (≤912 Å), the Strömgren radius, and the speed of light, respectively. Because \( R_S \) is nearly equal to \( R_m \) in the geometry of our model, we approximate \( U \) by substituting \( R_S = R_m \). We impose a flat prior for \( U \) in the range of \(-5 \leq \log U \leq -0.5\).

2.2.5. Other Model Specifications

Our models are truncated at a neutral hydrogen column density \( N_H = 10^{21} \) cm\(^{-2}\). We normalize the output emission line fluxes relative to the model Hβ flux for convenience of calculation.

2.3. Markov Chain Monte Carlo Methods

To estimate the best-fit parameters, we combine our CLOUDY photoionization models with MCMC methods. To run the MCMC methods, we use emcee (Ferland et al. 2013), a Python implementation of an affine invariant MCMC sampling algorithm. We use the log-likelihood Gaussian function in our MCMC methods. Our log-likelihood function \( \ln L \) is

\[ \ln L = -\frac{1}{2} \sum_{\lambda} \left( \frac{F_{\lambda,obs} - F_{\lambda,mod}}{\sigma_{\lambda,obs}} \right)^2 + \ln(2\sigma_{\lambda,obs}), \]

where \( \Lambda, F_{\lambda,obs}, F_{\lambda,mod}, \) and \( \sigma_{\lambda,obs} \) are the set of emission lines used, the observed emission line flux at wavelength \( \lambda \), the model emission line flux at wavelength \( \lambda \), and the observed error of the emission line at wavelength \( \lambda \), respectively. \( F_{\lambda,mod} \)
in Equation (6) is given by

$$F_{\lambda, \text{mod}} = \frac{N_{H, \lambda}}{N_{H, \text{cloudy}}},$$

where $F_{\lambda, \text{cloudy}}$ and $N_{H, \lambda}$ are the output of CLOUDY for the emission line flux at the wavelength $\lambda$ and the normalization factor for an H$\beta$ emission line, respectively. $F_{\lambda, \text{cloudy}}$ values are normalized at $F_{H, \lambda, \text{cloudy}} = 1$ by default in CLOUDY. We introduce $N_{H,\lambda}$ as a new free parameter to scale the model fluxes to the observed fluxes. We allow $N_{H,\lambda}$ (i.e., $F_{H,\lambda,\text{mod}}$ by definition) to vary within a range of 30$\sigma_{H,\lambda,\text{obs}}$ from $F_{H,\lambda,\text{obs}}$. Here, $F_{\lambda, \text{obs}}$ values are normalized at $F_{H,\lambda,\text{obs}} = 100$ as shown in Table 2. We have a total of seven free parameters in our photoionization models. As a prior probability distributions for each model parameters, we adopt a simple uniform distributions in the range permitted for each variable. We summarize the prior distributions for all free parameters in Table 3.

We initialize the positions of the parameters by randomly selecting values from the prior distributions. We use 40 walkers and let each chain run for 1000 steps. We define the “best-fit” parameter set as a parameter set with the maximum likelihood value in the sampled parameter sets. The uncertainty is defined by the range between the minimum and maximum values of the parameter sets that satisfy a condition

$$\ln L \geq \ln L_{\sigma},$$

$$\equiv -\frac{1}{2} \sum_{\lambda \in \Lambda} \left( \frac{3\sigma_{\lambda, \text{obs}}}{\sigma_{\lambda, \text{obs}}} \right)^2 + \ln(2\pi\sigma_{\lambda, \text{obs}}^2).$$

Note that this uncertainty is only a rough standard, and the actual uncertainty could be more strictly given.

### 3. Results

#### 3.1. Posterior Probability Distribution Functions

We obtain the best-fit parameters for all three galaxies in our sample using the method described in Section 2. We present the posterior probability distribution function (PDF) triangles for J1631+4426, J104457, and I Zw 18 NW in Figures 2–4, respectively.

One-dimensional and two-dimensional PDFs are plotted on the diagonal and off-diagonal, respectively. The gray scale in each of the two-dimensional PDFs represents the probability density of the sampled parameters. The darker region on the two-dimensional PDFs indicates a higher density of the sampled parameter sets. The red lines (the black dashed lines) indicate the values of the best-fit parameters (uncertainty ranges). The yellow dots are the sampled parameter sets within the uncertainty ranges. We summarize the best-fit parameters and their uncertainties in Table 4.

In Figures 2–4, the prior ranges are wide enough to reveal the overall shapes of the PDFs that are not distorted by the prior boundaries except for that of log $d_{\min}$ of J104457. However, the uncertainty ranges for log $d_{\min}$ of J104457 are within its prior range. The PDF for some of the parameters has multimodal distribution. In contrast, parameter sets within the uncertainty ranges (yellow dots) are concentrated around the best-fit parameters. This suggests that peaks other than those of the best-fit parameters are just the local maxima of Equation (6). The best-fit values for the metallicity of our three galaxies are comparable (within 0.2 dex) with the literature values of metallicity.

#### 3.2. Reproduction of Emission Lines

We compare the observed emission line fluxes with the model emission line fluxes reproduced with the best-fit parameters. In Figure 5, we present the normalized differences between the observed and the model fluxes for emission lines in the black dots. We also plot the 1$\sigma$ and 3$\sigma$ ranges for the emission lines in the red and yellow bars, respectively. From Figure 5, we find that the best-fit models simultaneously reproduce all the emission lines within around 3$\sigma_{\lambda, \text{obs}}$ for all of our three galaxies. Interestingly, [O iii] $\lambda$4363 is the most deviant line for J1631 +4426. This deviation is probably because our current model for the MCMC method could be weighting too much on reproducing [O iii] $\lambda$4959,5007. The 1$\sigma$ values for [O iii] $\lambda$4959,5007 are about 1% of the flux values, while the 1$\sigma$ values for [O iii] $\lambda$4363 are about 5% of the flux value.

#### 3.3. Ionizing Spectrum Shapes

In Figure 6, we depict the general ionizing spectrum shapes reproduced from the best-fit parameters for our three galaxies. Hereafter, we call these ionizing spectra as the “best-fit” ionizing spectra. For comparison, we overplot the ionizing spectrum of the BPASS binary model at the stellar age 10 Myr and the stellar metallicity $Z_\odot$ at 0.05 $Z_\odot$. We use BPASS v2.2.1 (Eldridge et al. 2017; Stanway & Eldridge 2018) with a Kroupa initial mass function (IMF) and a high mass cutoff at 300 $M_\odot$. All ionizing spectra are normalized at 910 Å. We also plot the uncertainties for the spectral fluxes at the ionization energies of the ions used in our parameter search. The uncertainty bars are given by the maximum and the minimum spectral flux values reproduced with the sampled parameter sets satisfying Equation (8). We note again that these uncertainties are only rough standards, and the actual uncertainties could be more strictly given.

Between the ionization energies of H$^0$ (13.6 eV) and He$^+$ (54.4 eV), we find that the best-fit ionizing spectra have two types of general spectrum shapes. The best-fit ionizing spectrum for J104457 has a convex upward spectrum shape like the one for BPASS binary models, except that most of the He II ionizing photons are absorbed by the stellar atmosphere in the BPASS binary models. On the other hand, the best-fit ionizing spectra for J1631 +4426 and I Zw 18 NW have convex...
downward spectrum shapes that BPASS binary models cannot reproduce. These convex downward spectrum shapes have dominant contributions from the power-law radiation around the ionization energy of He\(^+\) (54.4 eV). These two types of general spectrum shapes indicate a diversity of the ionizing spectrum shapes for EMPGs.

3.4. Comparison with Other Models

O21 claim that the combination of a BPASS binary model and blackbody radiation can reproduce emission lines from J104457 in a self-consistent manner. We compare our self-consistent model for J104457 with the model for J104457 presented in O21. We construct a mock model for the model presented O21 using the model parameters listed in the bottom column of Table 5 in the same paper. We use the same BPASS version and initial mass function as O21 for the mock model. In Figure 7(a), we present a spectrum of the mock model by the blue line, the spectrum from O21 by the green line, and our result for J104457 by the red solid line. Only the spectrum for below 54.4 eV is shown for the model in O21. We find that the

Figure 2. Posterior PDF triangles for J1631+4426. One-dimensional PDFs are shown along the diagonals, while two-dimensional PDFs are shown on the off-diagonals. The darker regions on the two-dimensional PDFs indicate the higher density of the parameter sets. The red lines (black dashed lines) indicate the values of the best-fit parameters (uncertainty ranges). The yellow dots are the sampled parameter sets within the uncertainty ranges.
spectrum in O21 has relatively higher fluxes around 54.4 eV than the spectrum of our result.

In Figure 7(b), we show the emission line fluxes and emission line ratios for the mock model (our model) as blue (black) dots. The mock model of O21 reproduces the observed He II λ4686 fairly well. However, other emission lines, especially the low-ionization emission line fluxes such as \([\text{O II}]\)λλ3727,3729, He I λ4026, and He I λ4471, are systematically underproduced, unlike our result. One possible explanation for this underproduction by the mock model is that the general spectrum shape for the mock model has a relatively lower ratio of low-energy (13.6–24.6 eV) fluxes to high-energy (35.1–54.4 eV) fluxes than that of our result.

Next, we consider how taking \([\text{Ne V}]\) emission lines into consideration affects our result. \([\text{Ne V}]\) emission lines are detected in some of the He II emitting EMPGs including J104457 (e.g., Izotov et al. 2004, 2021a; Senchyna et al. 2017; Isobe et al. 2022). Because \([\text{Ne V}]\) is a very-high-ionization line with an ionization potential of 97.1 eV, its relative flux to Hβ can be used to constrain the contribution of very hard (i.e., X-ray) radiation to the ionizing spectrum shapes (e.g., Lebouteiller et al. 2017; Senchyna et al. 2020; Simmonds et al. 2022).

Figure 3. Posterior PDF triangles for J104457. One-dimensional PDFs are shown along the diagonals, while two-dimensional PDFs are shown on the off-diagonals. The darker regions on the two-dimensional PDFs indicate the higher density of the parameter sets. The red lines (black dashed lines) indicate the values of the best-fit parameters (uncertainty ranges). The yellow dots are the sampled parameter sets within the uncertainty ranges.
et al. 2021). Simmonds et al. (2021) show that some ULX models can reproduce He II $\lambda$4686 and [Ne V] $\lambda$3426 flux values that are comparable to those from observations.

We conduct the same method as described in Section 2, but add [Ne V] $\lambda$3426 into consideration. We only examine for J104457 because [Ne V] emission lines are not detected in the other two galaxies, most likely due to the lack of sensitivity. To avoid uncertainty in the abundance ratio, we use [Ne V] $\lambda$3426/[Ne III] $\lambda$3869 as we have done to [S II] $\lambda\lambda$6316,6731. The observed [Ne V] $\lambda$3426/[Ne III] $\lambda$3869 value and its 1 $\sigma$ error for J104457 are 0.00347 ± 0.00315 (B21). We obtain similar best-fit values for each parameter from MCMC. In Figure 7, we have overplotted the ionizing spectrum produced from the parameter in Table 5 as the red dashed line. Although the blackbody component has a higher temperature, the newly obtained ionizing spectrum generally has a similar spectrum shape as the one we obtain without considering [Ne V] $\lambda$3426/[Ne III] $\lambda$3869. The [Ne V] $\lambda$3426/[Ne III] $\lambda$3869 value produced from new ionizing spectrum shapes is produced within around 3$\sigma$ of the observed value. Moreover, this new ionizing spectrum shape produces other emission lines within around 3$\sigma$. Therefore, we confirm that the general spectrum shape for
J104457 is consistent with [Ne V]λ3426, which requires very-high-energy (>97.1 eV) ionizing photons.

4. Discussion

4.1. Contributions from Stellar Radiation

Our best-fit ionizing spectra have blackbody temperature around (3–5) × 10^4 K. B-type (O-type) stars have surface temperatures of (1–3) × 10^4 K (≥3 × 10^4 K). This suggests that blackbody radiation in our best-fit ionizing spectra, especially that of J104457, can be explained by B- and O-type stars. However, the convex downward spectra of J1631+4426 and I Zw 18 NW suggest that contributions from stars to hard photons around 35.1–54.4 eV might not be as significant as expected in BPASS binary models. Stellar models including fast-rotating stars (e.g., Kubatová et al. 2019) and Population III stars (e.g., Grisdale et al. 2021) also have convex upward spectra around 13.6–54.4 eV, unlike our results. These mismatches suggest that hard radiation from stellar sources cannot solely explain He II ionizing photons for the two of our galaxies with convex downward spectrum shapes.

We also note that our general spectrum shapes do not take account stellar absorption. Stellar absorption weakens the intrinsic stellar radiation above ionization energies of H^0 (13.6 eV), He^0 (24.6 eV), and He^+ (54.4 eV). This raises the question of whether stellar models with stellar absorption can really reproduce ionizing spectra of our three galaxies, including the blackbody-dominated spectra of J104457. More sophisticated spectral modeling is needed to further examine the stellar contributions, but this is beyond the scope of our paper.

4.2. Contributions from Black Holes

We examine the contributions from black holes (BHs) such as in AGNs and HMXBs/ULXs. BHs can produce very hard radiation through nonthermal radiation from Comptonization/synchrotron radiation. Because nonthermal radiation has a power-law-like shape, radiation from a BH could explain the power-law-like component seen in the ionizing spectrum of J1631+4426 and I Zw 18 NW. BH radiation also has hot (≥10^5 K) thermal radiation from their accretion disks.

Temperatures of accretion disks are roughly proportional to M_BH^{-1/4}, where M_BH is the mass of BH. Following the relation between the accretion disk temperature and M_BH, intermediate-mass BHs (10^2 < M_BH < 10^5 M⊙) and less massive ones would not produce sufficient ionizing photons in the soft energy range of <54.4 eV. For this reason, we will first examine if an AGN can solely account for the general spectrum shapes of our three galaxies by comparing them with spectra of AGNs. Then, we will investigate whether the combinations of a BH and stellar population can explain the general spectrum shapes of our three galaxies.

4.2.1. Only BHs

The inner-disk temperature T_in of the accretion disk is around 10^5–10^6 K for AGNs. The blackbody radiation from the inner disk of an AGN gives a big blue bump (BBB) feature in the UV range of the ionizing spectrum. The BBB feature combined with nonthermal radiation can produce a spectrum shape like the one reproduced from the combination of blackbody and power-law radiation. We compare the shapes...
of four different AGN spectra with the general spectrum shapes of our three galaxies in Figure 8. These four AGN spectra are taken from Ferland et al. (2020), and they represent mean spectra of observed Type-1 AGNs grouped by Eddington ratios (Highest, High, Intermediate, and Low). As shown in Figure 8, all four AGN spectra have power-law like shapes between 13.6 and 54.4 eV, unlike the ionizing spectra of our three galaxies. The deformation of a disk blackbody by Comptonization in observed AGNs might be the reason why AGN spectra do not have blackbody-like shapes in 13.6–54.4 eV (see Ferland et al. 2020). From this comparison, we cannot conclude that AGNs can solely explain the general spectrum shapes for our three galaxies. However, we note that the ionizing spectrum shapes of AGNs remain unclear especially around the Lyman limit to soft X-rays because of intervening absorption.

4.2.2. BHs and Stars

We will explore the combinations of BHs and stellar sources to see if they can account for the general spectrum shapes of our three galaxies. We choose ULXs as nonstellar sources because they are popular candidates for the origin of He II. Moreover, there are detections of a ULX in I Zw 18 through X-ray observations (e.g., Kaaret & Feng 2013). As a ULX spectrum, we use a spectral model described in Gierliński et al. (2009). According to Simmonds et al. (2021), this ULX spectral model reproduces emission line ratios in metal-poor galaxies better than other ULX spectral models. We produce the ULX spectrum models from numerical calculations. To run the numerical calculations, we have referred to the code of the DISKIR model provided in XSPEC (Arnaud 1996). As presented in Simmonds et al. (2021), ULX spectral models cannot produce enough photons in UV region; thus we combine a ULX spectral model with a stellar spectral model (hereafter ULX + BPASS single model). We use spectra
reproduced from BPASS single-star models as stellar spectra. We assume a single-aged stellar population with the same IMF as the BPASS binary model we presented in Figure 6. We do not use BPASS binary models because adding extra hard components from a ULX would not alter the convex upward spectrum shape of the spectra reproduced from BPASS binary models. We use fluxes at the ionization energies of H0, He0, O+, and He+ for the best-fit ionizing spectra to restrict the ULX + BPASS single models for our three galaxies. We allow a stellar age $t$ and a ratio between 0.5 and 8 keV of the X-ray luminosity $L_X$ to the SFR ($L_X$/SFR). An SFR for $L_X$/SFR is calculated from the UV luminosity at 1500 Å using the relationships presented in Kennicutt (1998). For each of our three galaxies, we fix the value of the stellar metallicity $Z_*$ at the best-fit value of the gas-phase metallicity.

In Table 6, we summarize the parameters of the ULX + BPASS single models that reproduce the general spectrum shapes for our three galaxies. We compare the general spectrum shapes with the ULX + BPASS single-star models in Figure 9.

![Figure 7](image1.png)

**Figure 7.** Comparison between our result for J104457 and other models. (a) The blue, green, red solid, and red dashed lines are the spectrum of the mock model for O21, the model in O21, our result for J104457, and our result when we include [Ne V]3426/[Ne III]3869, respectively. Only the spectrum below 54.4 eV is shown for the model in O21. The other symbols are the same as those in Figure 6. (b) Emission line fluxes and emission line ratios from two models. The blue (back) dots are the emission line fluxes and emission line ratio from the mock model of O21 (our result for J104457). The other symbols are the same as those in Figure 5.

![Figure 8](image2.png)

**Figure 8.** Comparison of our result with AGN spectra. The dashed–dotted lines represent the mean AGN spectra at different Eddington ratios (Highest, High, Intermediate, and Low) taken from Ferland et al. (2020). The other symbols are the same as those in Figure 6.

![Figure 9](image3.png)

**Figure 9.** ULX + BPASS single models for J1631+4426 (red thin line), J104457 (blue thin line), and I Zw 18 NW (orange thin line). The other symbols are the same as those in Figure 6.

| Name of the Galaxy | $t$ (Myr) | $\log L_X$/SFR (erg s$^{-1}$/M$_\odot$ yr$^{-1}$) |
|--------------------|-----------|-----------------------------------|
| J1631+4426         | 8.2       | 40.7                              |
| J104457            | 2.2       | 41.5                              |
| I Zw 18 NW         | 8.5       | 41.0                              |

**Table 6.** Parameters for ULX + BPASS Single Models

Note. (1): Stellar age. We assume a single-aged stellar populations. (2): 0.5–8 keV X-ray luminosity to SFR.
reproduce the general spectrum shape of the best-fit ionizing spectra between 13.6 and 54.4 eV for our three galaxies, despite the diversity in the general spectrum shapes. For both types of the spectrum shapes, the $L_x$/SFR values are $\lesssim 10^{30} \text{ erg s}^{-1}/M_\odot \text{ yr}^{-1}$, which are comparable to the values obtained in Simmonds et al. (2021). The blackbody-like spectrum shape of J104457 can be explained by prominent stellar contributions relative to that of the ULX, while the convex downward spectrum shapes of J1631+4426 and I Zw 18 NW can be explained by the less prominent stellar contributions around 35.1–54.4 eV than that of J104457. Moreover, the stellar component for J104457 has a stellar age around 2 Myr, while the stellar components for J1631+4426 and I Zw 18 NW have a stellar age above 5 Myr. This suggests that the diversity of the spectrum shapes can arise from the stellar age difference of the stellar components. The stellar contributions become less prominent at $\gtrsim 5$ Myr because massive stars with masses $\gtrsim 40 M_\odot$ already reach their lifetimes (Xiao et al. 2018).

4.3. Other Possibilities

We have only examined the ULX as a nonstellar component when considering the combination with the stellar component, but it does not limit the possibilities of other sources such as low-luminosity AGNs and supersoft X-ray sources. Photoionization by shocks is still not ruled out from the candidate by our analysis. The ionization of He II by soft X-rays from cluster winds and superbubbles also remains a possibility (see Oskinova & Schaerer 2022). Further X-ray observations for J1631+4426 and J104457 may enable us to constrain contributions from X-ray emitting sources.

4.4. Multiband Comparison and Relation with Cosmic Reionization

We investigate the consistency between our ionizing spectrum shapes and the observed values of I Zw 18, where multiband data in the X-rays to optical photometry data are available. We assume that I Zw 18 has the same ionizing spectrum shape as our result for I Zw 18 NW to compare the model with the observed values of I Zw 18 as a whole. We use the X-ray luminosity obtained by the X-ray Multi-Mirror Mission (Kaaret & Feng 2013; Lebouteiller et al. 2017). For optical photometry, we use the SDSS $i'$- and $z'$-band magnitudes from DR16 (Ahumada et al. 2020) for I Zw 18 NW and I Zw 18 SE to compare the fluxes of the continuum. We do not use photometry data in other bands, where many strong emission lines are detected. To compare the optical photometry data, we replace the blackbody component of the ionizing spectrum with the BPASS single-star model reproduced with the parameters for I Zw 18 NW in Table 6. We normalize the luminosity by adopting a distance of 18.2 Mpc (Aloisi et al. 2007), an $\text{H} \beta$ luminosity of $10^{39.43} \text{ erg s}^{-1}$, and a relation between the number of hydrogen ionizing photons produced per second and the $\text{H} \beta$ luminosity presented in Ono et al. (2010). We show the comparison between the multiband data and the comparison model in Figure 10. The black diamonds represent unfolded X-ray luminosities and the leftward (rightward) black circle represents the $i'$- ($z'$-) band magnitude. The incident (net transmitted) spectrum of the comparison model is shown in the yellow (green) line. Here, the net transmitted spectrum is the sum of attenuated incident radiation and the outward portion of the emitted continuum and lines. The orange line is the same ionizing spectrum for I Zw 18 NW as the one presented in Figure 6. From Figure 10, we find that the optical photometry data is slightly below what our comparison model predicts. However, the net transmitted spectrum of our comparison model is consistent with the X-ray luminosities.

As described in Section 1, a nearby EMPG can be a probe for young galaxies at the EoR. We evaluate the contribution of X-ray photons from the young galaxies to cosmic reionization, assuming that the young galaxies have the same ionizing spectrum shapes as the spectrum of I Zw 18. We adjust the ionizing photon escape fraction of 20% to match the standard picture of cosmic reionization (e.g., Ouchi et al. 2009; Robertson et al. 2013). To do so, we consider the model spectrum that linearly combines the incident ionizing spectrum and the net transmitted spectrum with their luminosities multiplied by 0.2 and 0.8, respectively. In Figure 11, we depict the cumulative fraction of the hydrogen ionizing photon number at each energy in the red line. As shown in Figure 11, about 90% (97%) of the ionizing photons have energy below 24.6 eV (54.4 eV). Moreover, the contributions of the high-energy ($>54.4$ eV) photons will be further reduced because the photoionization cross-section has a photon energy dependency of approximately $E^{-3}$ (Osterbrock & Ferland 2006). Thus, we conclude that the hard ionizing radiation does not affect the standard picture of cosmic reionization (Robertson 2021).

5. Conclusions

We have searched for the general spectrum shapes of ionizing sources in EMPGs that can explain major emission lines including He II. We have prepared parameterized ionizing spectra with generalized shapes and use these ionizing spectra in photoionization models with free parameters of ionizing spectra and nebulae. For three EMPGs with strong He II 4686, we have determined seven parameters of the ionizing spectra and nebulae using MCMC methods.
Our main findings can be summarized as follows:

1. We have determined the best-fit parameters for our three galaxies. All the best-fit parameters are comparable to ordinary values. With the best-fit parameters, we successfully reproduced all major emission lines within \( \pm 3\sigma \) errors.

2. The ionizing spectrum produced from the best-fit parameters for J104457 has a blackbody-dominated shape around 13.6–54.4 eV with blackbody temperature \( 5 \times 10^{4} \) K. In contrast, the ionizing spectra for J1631+4426 and I Zw 18 NW have significant contributions from power-law radiation around 54.4 eV, with relatively low-temperature \( (3 \times 10^{5} \) K) blackbody radiation. As a result, the general spectrum shapes for J1631+4426 and I Zw 18 NW have convex downward shapes around 13.6–54.4 eV, which are fundamentally different from the shapes predicted by BPASS binary models. These two types of spectrum shapes indicate a diversity in ionizing spectrum shapes in EMPGs.

3. We compare the obtained general shapes of ionizing spectra with those of the ionizing spectra from stars, AGNs, and ULXs. We find that ULX + BPASS single-star models can explain the general shapes of the obtained ionizing spectra for our three galaxies. Furthermore, we show that the diversity of the spectrum shapes can be attributed to the differences in the stellar age.

4. We confirm that our result is consistent with the X-ray and optical photometry data for I Zw 18, for which the multiwavelength data are available. We also find that the hard ionizing radiation inferred from our general spectrum shape of I Zw 18 does not contradict the standard picture of cosmic reionization.

Spectroscopic observation of J1631+4426 and I Zw 18 NW for optical [Ne V] emission lines with high sensitivity would also be helpful in terms of constraining contributions of ionizing photons \( \gtrsim 100 \) eV in He II emissions. Our new analysis method would provide new insights into the statistical nature of EMPGs if applied to a sample with a large number of EMPGs.

We thank Wako Aoki, Yoshihisa Asada, Kohei Inayoshi, Akio Inoue, Carolina Kehrig, Tomoya Kinugawa, Haruka Kusakabe, Vianney Lebouteiller, Daniel Schaefer, Yuta Tarumi, and Masayuki Umemura for sharing their data and figures and giving us helpful comments. This research is based in part on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. We are honored and grateful for the opportunity of observing the Universe from Maunakea, which has the cultural, historical, and natural significance in Hawaii. This work is supported by the World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan, as well as KAKENHI Grant-in-Aid for Scientific Research (A) (20H00180, and 21H04467) through the Japan Society for the Promotion of Science (JSPS). This work was supported by the joint research program of the Institute for Cosmic Ray Research (ICRR), University of Tokyo. Numerical computations were in part carried out on Cray XC50 at Center forComputational Astrophysics, National Astronomical Observatory of Japan.

References

Abazajian, K., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2004, AJ, 128, 502

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297

Ahumada, R., Prieto, C. A., Almeida, A., et al. 2020, ApJS, 249, 3

Alavi, A., Colbert, J., Teplitz, H. I., et al. 2020, ApJ, 904, 59

Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, ApJS, 178, 20

Aloisi, A., Clementi, G., Tosi, M., et al. 2007, ApJL, 667, L151

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009,ARA&A, 47, 481

Atek, H., Richard, J., Kneib, J.-P., & Schaerer, D. 2018, MNRAS, 479, 5184

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5

Berg, D. A., Chisholm, J., Erb, D. K., et al. 2019, ApJL, 878, L3

Berg, D. A., Chisholm, J., Erb, D. K., et al. 2021, ApJ, 922, 170

Berg, D. A., Erb, D. K., Auger, M. W., Pettini, M., & Brammer, G. B. 2018, ApJ, 859, 164

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, ApJ, 811, 140

Dopita, M. A., Fischera, J., Sutherland, R. S., et al. 2006, ApJS, 167, 177

Eldridge, J. J., Stanway, E. R., Xiao, L., et al. 2017, PASA, 34, e058

Ferland, G. J., Chatszikos, M., Guzmán, F., et al. 2017, RMxAA, 53, 385

Ferland, G. J., Done, C., Jin, C., Landt, H., & Ward, M. J. 2020, MNRAS, 494, 5917

Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, RMxAA, 49, 137

Fernández, V., Amorín, R., Pérez-Montero, E., et al. 2022, MNRAS, 511, 2515

Gierliński, M., Done, C., & Page, K. 2009, MNRAS, 392, 1106

Grevesse, N., Asplund, M., Sauval, A. J., & Scott, P. 2010, ApSS, 328, 179

Grisdale, K., Thatte, N., Devriendt, J., et al. 2021, MNRAS, 511, 5517

Guseva, N. G., Izotov, Y. I., & Thuan, T. X. 2000, ApJ, 531, 776

Harikane, Y., Ouchi, M., Ono, Y., et al. 2016, ApJ, 821, 123

Ishibe, Y., Ouchi, M., Kojima, T., et al. 2021, ApJ, 918, 54

Isobe, Y., Ouchi, M., Suzuki, A., et al. 2022, ApJ, 925, 111
