A Spectroscopic Study of a Rich Cluster at $z = 1.52$ with Subaru and LBT: The Environmental Impacts on the Mass–Metallicity Relation

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Abstract

We present the results of our near-infrared spectroscopic observations of a rich cluster candidate around a radio galaxy at $z = 1.52$ (4C65.22) with Subaru/MOIRCS and Large binocular telescope/LUCI. We observed 71 galaxies mostly on the star-forming main sequence selected by our previous broadband (photo-$z$) and narrowband H$\alpha$ imaging observation in this cluster environment. We successfully confirmed the redshifts of 39 galaxies, and concluded that this is a gravitationally bound, real cluster at $z = 1.517$. Our spectroscopic data also suggest a hint of large-scale filaments or sheet-like three-dimensional structures crossing at the highest-density cluster core. By stacking the spectra to derive their average interstellar medium gas-phase metallicity based on the [N II]/H$\alpha$ emission line flux ratio, we find that the mass–metallicity relation (MZR) in the 4C65.22 cluster environment is consistent with that of H$\alpha$-selected field galaxies at similar redshifts. Our results suggest that the environmental impacts on the MZR is small at high redshifts, but a larger sample of high-$z$ clusters and their member galaxies is still required to fully address the effect of environment as well as its cluster–cluster variation.

Key words: galaxies: evolution – galaxies: clusters: individual (4C65.22) – galaxies: ISM – techniques: imaging spectroscopy

1. Introduction

Galaxy properties are characterized by a number of parameters such as, e.g., stellar mass ($M_*$), star formation rate (SFR), color, or interstellar medium (ISM) gas-phase metallicity, and many studies have attempted to identify potential links between these parameters. A large sample of galaxies drawn by recent large surveys covering a huge area on the sky (like Sloan Digital Sky Survey; SDSS, York et al. 2000) allowed us to unveil many fundamental correlations between the physical parameters. One of the most prominent examples is the tight correlation between $M_*$ and SFR for star-forming galaxies; so-called star formation main sequence (SFMS; Brinchmann et al. 2004; Peng et al. 2010). The correlation between $M_*$ and galaxy ISM gas-phase metallicity, which is often called the mass–metallicity relation (MZR), is also well established in the local universe (e.g., Tremonti et al. 2004).

The environment of galaxies is thought to be another important parameter that influences galaxy properties. In the local universe, the central regions of galaxy clusters are in general dominated by red, passive galaxies, while blue, star-forming galaxies are mainly located in their outskirts (e.g., Dressler 1980; Gómez et al. 2003; Goto et al. 2003; Balogh et al. 2004; Tanaka et al. 2004). It is reported that the SFMS does not significantly change with environment in the local universe (Peng et al. 2010), and similarly, it is reported that MZR shows little environmental dependence at least in the local universe (e.g., Cooper et al. 2008; Ellison et al. 2008; Wu et al. 2017).

However, the correlations between galaxy properties established in the local universe are not necessarily applicable to galaxies in the distant universe, where the cosmic SFR density is much higher than the present-day universe (Hopkins & Beacom 2006). Our next important step is therefore to investigate the evolution of those relationships and understand how the correlations are formed and maintained across cosmic time and environment. Some authors have studied the evolution of the SFMS and/or MZR, and it is shown that the SFMS already exists at the very early epoch up to $z \sim 6$ (e.g., Salmon et al. 2015; Tomczak et al. 2016; Santini et al. 2017), and the MZR is also shown to exist up to $z \sim 3.5$ (e.g., Erb et al. 2006; Maiolino et al. 2008; Troncoso et al. 2014; Onodera et al. 2016; Sanders et al. 2018).

Considering the well-known, increasing fraction of star-forming galaxies in higher-redshift cluster environments (Butcher & Oemler 1984; van Dokkum et al. 2000), one might expect that environmental effects on galaxy properties could be weaker in the more distant universe. However, it is always difficult to construct a large, uniform sample of galaxies in the distant universe, and it prevents us from unveiling the environmental variation (if any) in the fundamental correlations between galaxy properties at high redshifts. Although some authors studied the environmental dependence of the SFMS by comparing star-forming galaxies in high- and low-density environments (e.g., Vulcani et al. 2010; Li et al. 2011; Koyama et al. 2013), a full consensus has not yet been obtained.

Furthermore, because ISM gas-phase metallicity measurement of distant galaxies requires a deep spectroscopy in near-infrared (NIR), it is much more difficult to investigate environmental dependence of MZR at high redshifts. There are only a limited number of observational studies discussing...
the environmental impacts on the MZR at the “cosmic noon” epoch (e.g., Kulas et al. 2013; Kacprzak et al. 2015; Shimakawa et al. 2015; Tran et al. 2015; Valentino et al. 2015; Maier et al. 2019), and interestingly, their conclusions are different from study to study. For instance, Kulas et al. (2013), Shimakawa et al. (2015), and Maier et al. (2019) investigated the ISM gas-phase metallicity of member galaxies of (proto-) clusters at $z = 1.5, 2.2, 2.3,$ and $2.5$. They suggested that the mean metallicity of low-mass cluster galaxies is higher than that of field galaxies with the same stellar mass. Kulas et al. (2013) and Shimakawa et al. (2015) claimed that this difference can be explained by the metal recycling of momentum-driven outflow; i.e., outflow from a star-forming galaxy returns to itself in a short timescale due to the higher pressure of surrounding intergalactic medium (IGM) in a denser environment. This mechanism would work more effectively on low-mass galaxies because their escape velocity is lower than that of high-mass galaxies and thus metal-enriched gas is easier to be blown out from less massive galaxies. On the other hand, Tran et al. (2015) and Kacprzak et al. (2015) suggest that there is no significant environmental dependence in the MZR at $z \sim 2$. They concluded that the environmental effect is, if present, small and not a primary factor. In addition, Valentino et al. (2015) investigated a galaxy cluster at $z = 1.99$ and claimed that the member galaxies of this cluster have lower ISM gas-phase metallicity than field galaxies at the same redshift. Their interpretation is that the inflow of pristine gas into a high-density environment would dilute the gas metallicity and enhance the specific SFR of galaxies residing in high-density environments.

In this paper, we present the results of our new spectroscopic observations for galaxies in another distant cluster at $z = 1.52$ (4C65.22). This cluster (candidate) was originally discovered by a photometric H$\alpha$ study of a radio galaxy field with Subaru (Koyama et al. 2014). They observed this region with broadband and narrowband (H$\alpha$) imaging with Subaru/MOIRCS (FoV: $7' \times 4'$, Ichikawa et al. 2006; Suzuki et al. 2008) and found 44 H$\alpha$ emitter candidates. In addition, by using the photometric redshifts (photo-$z$) derived with the optical (Subaru/Suprime-Cam; Miyazaki et al. 2002) and NIR (Subaru/MOIRCS) data, it was clearly shown that red-sequence galaxies (with $z' - J > 1.2$) are strongly clustered in the cluster central region ($\lesssim 200$ kpc), while blue galaxies ($z' - J < 1.2$) are located in its outskirts. They claimed that this is a good example of a “mature” cluster at this high redshift, although the cluster has not been spectroscopically confirmed so far. We performed a follow-up NIR spectroscopy of star-forming galaxies in this rich cluster environment with Subaru/MOIRCS and the Large Binocular Telescope (LBT)/LUCI. We first confirm the physical association of the cluster member galaxies in this field, and then we investigate the gas-phase metallicity (hereafter “metallicity” for simplicity) of those cluster member galaxies to discuss the environmental dependence of MZR at $z = 1.5$.

The structure of this paper is as follows. In Section 2, we show our sample selection and summarize the NIR spectroscopic observations with LBT/LUCI and Subaru/MOIRCS. In Section 3, we present the 2D distribution of cluster member galaxies and measure their gas-phase metallicity, and then discuss environmental dependence of MZR in Section 4. We summarize our results in Section 5. Throughout this paper, we adopt a flat $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and a Salpeter initial mass function (Salpeter 1955). These cosmological parameters give a $1''$ scale of 8.46 kpc and the cosmic age of 4.2 Gyr at the redshift of our target cluster ($z = 1.52$). Magnitudes are all given in the AB system.

### 2. Observation and Data

The aim of this study is to spectroscopically confirm the physical association of the strong overdensity of galaxies in the 4C65.22 field reported by Koyama et al. (2014), and to study the properties of galaxies in high-density environment at this high redshift. We performed NIR spectroscopic observations of 71 galaxies in the 4C65.22 field with LBT/LUCI (Seifert et al. 2003) and Subaru/MOIRCS (Ichikawa et al. 2006; Suzuki et al. 2008). Our primary targets are H$\alpha$ emitters and blue galaxies (star-forming galaxy candidates) identified by Koyama et al. (2014), because it is much harder to detect continuum emission and absorption lines of red galaxies without emission lines at this redshift. In Figure 1, we show the distribution of our H$\alpha$ emitter sample on the $M_*$–SFR plane. The red circles represent H$\alpha$-emitter candidates reported in Koyama et al. (2014), and the blue points indicate galaxies of which H$\alpha$ emission lines are detected by our spectroscopic observation. The histograms at the top and right-hand side show the normalized distribution of stellar mass and SFR of the HAEs (red) and our spectroscopic members (blue), respectively. Below, we describe the details of our observations.
Table 1

| Mask    | Exp. Time (min) | Seeing (arcsec) | Slit Width (arcsec) | N_{obj} |
|---------|-----------------|-----------------|--------------------|---------|
| LUCI-1  | 70              | ∼1.0            | 1.0                | 10      |
| LUCI-2  | 110             | ∼0.7            | 1.0                | 10      |
| LUCI-3  | 130             | ∼1.2            | 1.0                | 10      |
| MOIRCS-1| 180             | ∼0.5            | 0.8                | 33      |
| MOIRCS-2| 180             | ∼0.8            | 0.8                | 33      |

2.1. LBT/LUCI Spectroscopy

The NIR spectroscopic observation was carried out in 2014 May with LBT/LUCI; an NIR spectrograph and imager for LBT (Seifert et al. 2003). We used the multiobject slit (MOS) mode with 210_zHK grating with 1″ slit width, which gives a spectral resolution of $R \sim 3900$ over $\lambda = 1.55–1.74 \mu m$. We prepared three MOS masks, each of which includes 10 target galaxies. There are three galaxies observed with two masks, and the total number of our LUCI targets is 27. The exposure time for each configuration (LUCI-1, 2, and 3) is 70, 110, and 130 minutes, respectively, with a mean seeing size of ∼1″. Table 1 summarizes our observation.

We reduced the data using a custom-made pipeline, Pyroscope (developed by J. Kurk). The pipeline process includes bad pixels, cosmic-ray correction, distortion correction, wavelength calibration for each slit, sky subtraction, and flux calibration. With a visual inspection of the 2D spectra, we detected emission lines depending on the slit positions on the masks, some of the spectra do not cover the wavelength range of $\lambda \sim 1.65 \mu m$ (where we expect the H$\alpha$ lines of cluster member galaxies). For those galaxies, we instead try to identify emission lines over the range between $\lambda = 12175 \lambda$ and 13015 λ to look for the [O III] $\lambda 5007$ line for the same redshift. With this approach, we additionally identify three galaxies in this field.

2.2. Subaru/MOIRCS Spectroscopy

We also performed multiobject NIR spectroscopy of galaxies in the 4C65.22 field in 2015 May with Subaru/MOIRCS using $zJ500$ grism with 0′/8 slit width, which provides a spectral resolution of $R \sim 464$ over $\lambda = 0.9–1.78 \mu m$. We designed two MOS masks (with 33 objects for each), and the exposure time was 3 hr for each mask under the seeing conditions of 0′/5–0′/8 (see also Table 1). We note that 16 of the MOIRCS targets are overlapped with our LUCI targets, so that the number of galaxies observed only with Subaru/MOIRCS is 41.

The data reduction was performed using the MOIRCS spectroscopic pipeline, MCSMDP (Yoshikawa et al. 2010). The pipeline process includes flat-fielding, bad pixels, cosmic-ray correction, distortion correction, wavelength calibration for each slit, sky subtraction, combine, and flux calibration. By inspecting the reduced spectra, we determined the redshifts of 17 galaxies (for which significant emission lines are detected) in the same way as described in Section 2.1. We note that, depending on the slit positions on the masks, some of the spectra do not cover the wavelength range of $\lambda \sim 1.65 \mu m$ (where we expect the H$\alpha$ lines of cluster member galaxies). For those galaxies, we instead try to identify emission lines over the range between $\lambda = 12175 \lambda$ and 13015 λ to look for the [O III] $\lambda 5007$ line for the same redshift. With this approach, we additionally identify three galaxies in this field.

2.3. Final Sample

We successfully determined the redshifts of 39 galaxies in total: 19 from LUCI, 27 from MOIRCS, and 7 are observed with both. For the 7 galaxies observed with both LUCI and MOIRCS, we confirm that their redshifts derived from LUCI/MOIRCS data are consistent, suggesting no systematic bias between the data obtained with different telescopes/instruments. We show in Table 2 the full list of the spectroscopically confirmed cluster member galaxies in the 4C65.22 field and their basic properties.

We comment that we quote the $M_*$ and SFR derived by Koyama et al. (2014); they determined $M_*$ with $K$-band photometry with $M_*/L_{K,obs}$ correction based on the $z' - K_s$ color (see Equation 1 in Koyama et al. 2014), while they derived SFR with H$\alpha$ photometry. To measure the H$\alpha$ flux of individual galaxies, they first calculated the H$\alpha$+[N II] line flux, continuum flux density, and EW$_{rest}$ of each H$\alpha$ emitter from their broadband and narrowband imaging data. They derived the [N II]/H$\alpha$ line flux ratio from the H$\alpha$+[N II] equivalent width using the empirical relation for local star-forming galaxies established by Sobral et al. (2012). Then, they corrected for the dust attenuation effect with the SFR$_{H\alpha}$/SFR$_{UV}$ ratio (Buat 2003; Tadaki et al. 2013; see also Koyama et al. 2014) to finally derive SFR and sSFR of the H$\alpha$ emitter sample. We note that the [N II] correction and the dust extinction correction are the major sources of uncertainty when deriving the SFRs with this approach. Koyama et al. (2015) reported that the uncertainty associated with the dust extinction correction from the H$\alpha$/UV ratio is typically ∼0.4 mag. Also, Villar et al. (2008) showed that the scatter around the correlation between the H$\alpha$/[N II] ratio and the H$\alpha$+[N II] equivalent width is ∼0.2 dex. On the other hand, for the stellar mass estimate, we simply propagate the photometric errors of our $z$-band and $K_s$-band data. These uncertainties are shown with the red-line error bars in Figure 1.

We have mainly used the H$\alpha$ line for the redshift determination, but another important goal of this study is to investigate the metallicity of galaxies in this cluster region. In order to use N2 index (Pettini & Pagel 2004) for metallicity calibration (see Section 3.3), we choose galaxies whose [N II] $\lambda 6583$ emission line is not contaminated by strong OH night sky lines. We visually inspect the spectra of our final sample, and carefully select 19 galaxies from the LUCI sample and 12 galaxies from the MOIRCS sample, in which 5 galaxies are
observed with both instruments. We use these 26 “clean” galaxies when we study the environmental impacts on the MZR (Section 3.3). Here we note that we do not apply any aperture correction, because the results of this paper rely only on the Hα and [N II] λ6583 line flux ratio. We note that the seeing size is larger than the slit width for 10 galaxies observed with LUCI-3. This slightly degrades the quality (S/N of the spectra, but the line flux ratio should not be strongly affected.

Finally, we note that active galactic nuclei (AGN) can contribute to enhance their [N II] emission line fluxes, which might affect our metallicity measurement (N2 index, Pettini & Pagel 2004; see Section 3.3). In addition, it is also expected that AGN at these redshifts are often accompanied by strong outflow (Genzel et al. 2014). Because the S/N ratio of our MOIRCS sample is not so high, we are not able to rule out the possibility of AGN. For galaxies observed with LUCI, we carefully inspected each spectrum, and we confirm that there is no broad-line features with, e.g., FWHM ≥ 1000 km s⁻¹ or no extremely enhanced [N II] λ6583 emission lines in our sample. We therefore conclude that the effect from type-1 AGN is small, but we cannot eliminate the possibility of contamination from type-2 AGN. On the other hand, for the galaxies observed with MOIRCS, we examine the line flux ratios on the BPT diagram (e.g., Baldwin et al. 1981; Kewley et al. 2013) using the stacked spectrum (see Section 3.2). We find that the emission line flux ratios for both high mass (10¹⁰.⁴⁸ M☉ < M* < 10¹¹.⁴¹ M☉) and low mass (10⁹.⁰⁴ M☉ < M* < 10⁹.⁴¹ M☉) subsamples are consistent with H II (star-forming) galaxies on the BPT diagram at
and contamination from strong OH emission lines at the wavelengths of their Hα lines. The edge of the FoV, respectively.

The black and gray curves represent the transmission curve of the MOIRCS narrowband filter (NB 1657) used in Koyama et al. (2014) at the center and the edge of the FoV, respectively (see Section 2).

3. Result

3.1. Redshift Distribution and 2D map

We show in Figure 2 the redshift distribution of our spectroscopic sample. The blue and red histograms indicate the number of galaxies observed with LBT/LUCI and Subaru/MOIRCS, respectively. The magenta histogram shows the galaxies observed with both LUCI and MOIRCS. We use LUCI data for the galaxies observed by both LUCI and MOIRCS. The black solid curve drawn in Figure 2 is the average filter response function of the MOIRCS NB 1657 filter at the center of the field of view (FoV), while the dotted curves are the transmission at the edge of FoV (Tanaka et al. 2011); we note that the response function of the MOIRCS NB 1657 filter changes with the location within the FoV. It is now clear that zspec of galaxies in the 4C65.22 field are concentrated at z = 1.510–1.525 with very few outliers. This range is much narrower than the width of the narrowband filter (even if we take into account the wavelength shift of the filter transmission at the edge of the FoV), suggesting that these galaxies are in fact concentrated in this small redshift range and not randomly distributed.

In Figure 3, we show the 2D distribution of our spectroscopic sample. The triangles, squares, and circles indicate galaxies with spec-z determined by LBT/LUCI, Subaru/MOIRCS, and both of the instruments, respectively. The top and right panels show the projected distribution on the R.A.–z and decl.–z plane, respectively. It can be seen that the relatively high-z data points tend to be located in the cluster central region (or high-density regions), while the low-z data points tend to be located in the outskirts, suggesting that there are two large-scale filaments (or planes) crossing at the central region of the cluster. Such complicated large-scale structures are often seen in the nearby universe or in numerical simulations, and our data suggests that the situation seems to be similar around this newly discovered structure at z = 1.52.

To determine the redshift of the cluster by eliminating the effect of surrounding structures, we here focus on galaxies located in the very central region. By taking the median of the zspec for galaxies located within 1 arcmin from the density peak (corresponding to 500 kpc, green circle in Figure 3), we determine the redshift of this galaxy cluster to be z = 1.517. We note that there still remains an uncertainty for the estimate of the cluster redshift because eight red passive galaxies dominating the very central region of the cluster are not observed in this study (see Koyama et al. 2014).

3.2. Stacking and Fitting

We will discuss the metallicity of the cluster member galaxies and their environmental dependence in the next section. However, the signal-to-noise ratios of our data are not very high (typically S/N(Hα)∼4), and it is impossible to determine the metallicity of individual galaxies. We therefore apply stacking analysis to derive average metallicity for the carefully selected 19 galaxies observed with LUCI and the 12 galaxies observed with MOIRCS, whose Hα and [N II] lines are not contaminated by strong OH sky lines (we note that this includes 5 galaxies observed with both LUCI and MOIRCS). Also, to study the stellar mass dependence of the metallicity of cluster galaxies, we divide our sample into two equal-sized bins by the median stellar mass (at 1010.48 M☉ for LUCI and MOIRCS sample separately due to their different spectral resolution), and perform stacking analysis as described below for each subsample.

We first determine the continuum level of individual galaxies by applying the linear fitting to the spectrum around Hα except for emission lines, and subtract it from the individual spectrum. We then normalize the spectra by their Hα flux before stacking. We note that the details of the spectral stacking procedure are different from study to study. In particular, this flux normalization step is not performed in many studies. This step would not be necessary when we can assume that the galaxies used for stacking analysis have the same properties (e.g., in the case that the sample has same stellar mass), but it is expected that the results would be biased to galaxies with larger Hα flux. For example, since galaxies with large Hα flux are expected to have pristine gas which has less oxygen in general, this may lead to an underestimate of the mean metallicity of our sample.

Another possible method for the spectral stacking is to stack the spectra without normalization with Hα flux (but put a weight based on their background noise), but in this case, galaxies with strong Hα emission (hence with high S/N) would largely contribute to the results. Because our aim is to study environmental dependence of the metallicity (determined by the Hα/[N II] flux ratio) at fixed stellar mass, we decided to normalize the spectra based on the Hα flux.

9 The large errors for the log([O III]/Hβ) ratio are partly caused by the contamination from strong OH emission lines at the wavelengths of their Hβ and/or [O III] lines. We carefully removed the spectra whose Hα or [N II] lines are contaminated by OH emission lines from our analyses (see also Section 3.2), but we do not do this for the Hβ or [O III] lines to keep a reasonable sample size (and it is not a problem because we do not use Hβ or [O III] lines for the metallicity measurements in this study).
Finally, we stack the (normalized) spectra by calculating the mean flux density at each wavelength, weighted by the noise levels estimated in the original spectra (before normalization) because it represents the real quality of the spectra. We believe that the procedure described above is the best approach to study the mean Hα/[N II] flux ratio in this study, but we verified that our conclusions are not changed even if we stack the spectra without any normalization. Figure 4 shows our stacked spectra for each subsample.

We fit Hα and [N II]λ6583 lines of the stacked spectra with double Gaussian function (blue line in Figure 4) with the peak flux density and the velocity width of Hα and [N II]λ6583 as free parameters (assuming the velocity widths are the same for Hα and [N II]λ6583). We note that [N II]λ6548 is also covered in the range of our spectroscopy, but we do not use it in our fitting process because of its low S/N ratio.

3.3. MZR

The MZR is the correlation between galaxy stellar mass ($M_*$) and their oxygen abundance (e.g., Tremonti et al. 2004). In general, more massive galaxies tend to have higher metallicity, and the slope of the MZR becomes flatter in the massive end. Tremonti et al. (2004) suggested that the steepness of the MZR toward the low-mass end is related to the escape velocity of galactic outflow. Massive galaxies have deep potential wells (hence require large escape velocity), which results in the decrease/suppression of outflowing gas; in other words, for more massive galaxies, a larger fraction of outflowing gas/material driven by their star-forming activity returns to them. On the other hand, less massive galaxies have shallower potential wells and require smaller escape velocity. This scenario is consistent with the predictions of numerical simulations as well as some observational results (e.g., Erb et al. 2006; Finlator & Davé 2008; Davé et al. 2012; Onodera et al. 2016; Sanders et al. 2018). In addition, the gas fraction of galaxies is another important parameter that influences their gas-phase metallicity; i.e., gas-rich galaxies tend to have lower metallicity with higher SFR (e.g., Bothwell et al. 2013).

In this paper, we investigate environmental impacts on the chemical enrichment in (star-forming) galaxies in cluster environment at $z = 1.52$. It should be noted that there are many metallicity calibrators used for distant galaxies. In this paper, we use the [N II]/Hα method (Pettini & Pagel 2004) because of the limited wavelength coverage of our LUCI data. As we mentioned in the previous sections, we here use only 26 cluster member galaxies at $z = 1.52$ whose Hα and [N II]λ6583 are not contaminated by OH emission lines, in order to derive the average [N II]/Hα line flux ratio (see Sections 2.3; 3.2; Pettini & Pagel 2004).

We note that our sample is distributed over a wide stellar mass range. Some recent studies suggest that the environmental effect on MZR appears especially in the low-mass side (Kulas et al. 2013 and Shimakawa et al. 2015). To check this possibility, we divide our sample into the high- and low-mass subsamples based on their stellar mass (for LUCI and MOIRCS sample separately). Using the stacked spectrum of each subsample (see Figure 4), we calculate the N2 index, $N2 \equiv \log([NII] \lambda 6583/H\alpha)$, for each stacked spectrum. We then derive their mean metallicity with the equation of $12 + \log(O/H) = 8.90 + 0.57 \times N2$ (Figure 5).

In Figure 5, we compare the average metallicity of our sample with the MZR for general field galaxies at the same redshifts. The gray shaded region shows the MZR for field galaxies at $1.4 < z < 1.7$ derived by Zahid et al. (2014), and the black solid line shows the result at $0.8 < z < 1.4$ derived by Stott et al. (2013), respectively. We note that the redshift range of the galaxy samples used in Stott et al. (2013; 313 at $z = 1.47$ and 68 at $z = 0.84$) is slightly different from that of our sample, but we believe that we can use their results as a comparison sample for our cluster galaxies at $z = 1.52$. In general, using a different method of metallicity calibration can
produces different metallicity estimates. We here choose those two studies for our comparison, because they use the same metallicity calibration as our analysis (based on Pettini & Pagel 2004, N2 index) at similar redshifts. It can be seen that low-mass cluster galaxies \((10^{9.93}M_\odot < M_\ast < 10^{10.48}M_\odot)\) tend to be more metal-rich than those in the field environment derived by Zahid et al. (2014), while the MZR at the same redshifts shown by Stott et al. (2013) is almost flat, which is in good agreement with our results. We expect that this difference between these two MZR for field galaxies is caused by the different sample selection. We will discuss more in detail about the potential bias in Section 4.1.

4. Discussion

With large efforts to investigate the metallicity of galaxies in the high-z universe over the last decade, it is now established that the MZR exists in the high-z universe (Erb et al. 2006; Maiolino et al. 2008; Troncoso et al. 2014; Onodera et al. 2016; Sanders et al. 2018), which has also been reproduced by recent numerical simulations (Torrey et al. 2018). However, there are only countable studies on the environmental dependence of the MZR at high redshifts, and a consensus has yet to be reached on the environmental impacts on the chemical enrichment within the galaxies.

Kulas et al. (2013) and Shimakawa et al. (2015) showed that low-mass (proto-)cluster galaxies tend to have higher metallicity than those in the field environment. They interpreted this trend as a result of a high metallicity recycling rate caused by cluster gaseous IGM with high pressure. On the other hand, Tran et al. (2015) and Kacprzak et al. (2015) showed that there...
is no environmental dependence in the MZR. Kacprzak et al. (2015) also used hydrodynamical simulations to show that the metallicity of galaxies in cluster and field environments is comparable. In contrast, Valentino et al. (2015) have investigated the MZR in a cluster at \( z = 1.99 \) and claimed that cluster galaxies have lower metallicity than those in the field environment. Their interpretation is that inflowing pristine gas would lower the gas metallicity within the galaxies and boost their SFR at the same time.

In this paper, we have focused on star-forming galaxies in a newly confirmed galaxy cluster around the radio galaxy, 4C65.22, at \( z = 1.52 \). With LUCI and MOIRCS spectroscopy presented in this paper, our results suggest that low-mass star-forming galaxies in the 4C65.22 field have slightly higher metallicity than those in Zahid et al. (2014) but comparable to Stott et al. (2013; Figure 5). Below, we discuss which study is more appropriate for our comparison, and then we also discuss whether there is any environmental effect on the chemical enrichment in galaxies at this redshift.

### 4.1. Different Sample Selection

As shown in Figure 5, Stott et al. (2013) showed high metallicity in low-mass galaxies, implying a flat MZR, which is consistent with our results (black points and the connecting black line in Figure 5). On the other hand, MZR in Zahid et al. (2014; gray shade in Figure 5) shows a clear difference from our results and Stott et al. (2013) in particular at the low-mass end (\( 10^{10.93} M_\odot < M_\ast < 10^{10.49} M_\odot \)). We note that Stott et al. (2013) selected their targets primarily based on their New H\( \alpha \) imaging (HiZELS, \( z = 0.84-1.47 \); Sobral et al. 2013), while the targets in Zahid et al. (2014) are selected by the \( K \)-band magnitudes (\( K < 23 \) mag) and their broadband colors.

Stott et al. (2013) explained that the reason for the discrepancy between their results and MZRs shown by previous studies is the effect of dust attenuation in the photometric selection in the rest-UV and optical bands, which can miss dusty galaxies especially at the low-mass side. Because dusty galaxies tend to have higher metallicity, Stott et al. (2013) claimed that the MZR in previous studies can be biased toward the low metallicity galaxies at the low-mass end. Also, Stott et al. (2013) point out that the samples in the previous studies are biased toward the higher SFR. In general, galaxies with higher SFR tend to show lower metallicity (so-called Fundamental Metallicity Relation (FMR); Mannucci et al. 2010), most likely driven by the increasing amount of pristine inflowing gas.

In order to avoid these biases, Zahid et al. (2014) selected their sample using \( K \)-band magnitude and color–color plane. Zahid et al. (2014) claimed that the effect of dust attenuation would move the object parallel to their criteria on the color–color diagram, so that their sample is not affected by the dust compared with UV-selected galaxies used in the previous studies (Daddi et al. 2004). They also argued that their exposure time for each target is much longer than that in Stott et al. (2013), which enables them to observe galaxies down to lower SFRs. For these reasons, Zahid et al. (2014) conclude that their MZR and their suggestion on the redshift evolution of MZR should be valid.

Although the exact reason for the discrepancy between the results of these studies is unclear, we use the MZR of Stott et al. (2013) as the field sample compared with our results, because our original sample was selected with the narrowband H\( \alpha \) imaging survey performed by Koyama et al. (2014), i.e., the same method as Stott et al. (2013) for field galaxies. We note, however, that the choice of different field sample for the comparison can lead to a different interpretation on the environmental impacts on the MZR as shown in Figure 5.

### 4.2. FMR

Stott et al. (2013) fit the relation between the stellar mass, SFR, and the metallicity (FMR) of their sample at \( z = 0.8-1.47 \) using the two variable polynomial. The typical scatter around the best-fit relation for their sample (\( \sigma \)) is 0.2 dex. This is about a factor of two smaller than the scatter around the fundamental plane reported for local galaxies (Mannucci et al. 2010). Stott et al. (2013) suggested that the FMR evolves with redshift, while the original work by Mannucci et al. (2010) suggested that the FMR does not change over the cosmic time.

In order to evaluate the environmental effects on the chemical enrichment in galaxies in the 4C65.22 cluster field, we here calculate the metallicity offset from the FMR of Stott et al. (2013), \( \Delta [12 + \log (O/H)] = 12 + \log (O/H)_{\text{obs}} - (12 + \log (O/H)_{\text{obs}})_{\text{Stott et al. 2013}} \), and the results are shown in Figure 6.

We find that both low- and high-mass MOIRCS subsamples and the low-mass LUCI sample show \( \Delta [12 + \log (O/H)] < 1 \sigma \). The LUCI high-mass sample shows slightly larger deviation from the FMR of Stott et al. (2013), but it is still within the \( 2 \sigma \) level. Therefore, we consider that our sample has similar properties in their gas-phase metallicity to the field galaxies at similar redshifts. This can be interpreted as that the balance between the inflow and outflow in the dense environment would not be affected by global environment.

### 5. Summary

We present the results of our NIR spectroscopic observations with LUCI and MOIRCS of 71 star-forming galaxies in a high-redshift (\( z = 1.52 \)) galaxy cluster candidate discovered by Koyama et al. (2014). We successfully determined the
spectroscopic redshifts of 39 galaxies with Hα and [O III] λ5007 lines. We confirm the redshift of the central region in this cluster to be \(z = 1.517\) (<500 kpc from the peak of galaxy overdensity) and confirm that this is a real, physically associated, well-matured cluster at \(z = 1.517\). By mapping the 3D structures around the cluster, we find a hint that this cluster is located at the intersection of two filaments/sheet-like structures, and the large-scale structures may be extended even beyond our survey field.

We then divide our spectroscopic members of this cluster environment into two subsamples by the median of their stellar mass, at \(10^{10.48}\, M_{\odot}\) (for those observed with LUCI and MOIRCS separately). For each subsample, we performed stacking analysis after subtracting continuum and normalizing each spectrum by their Hα flux. We derived “mean” metallicity of each subsample without being affected by those with very strong OH sky lines. Using these stacked spectra and the commonly used N2 method developed by Pettini & Pagel (2004), we investigated the environmental dependence of gas-phase metallicity in galaxies at \(z \approx 1.5\). We note that our sample would not be strongly affected by type-1 AGNs, but we cannot rule out the possibility of some contamination from type-2 AGNs with the current data alone.

By comparing the MZR of our cluster sample to that of field galaxies at similar redshifts derived by Stott et al. (2013), we find that the metallicity of our targets is consistent with the field galaxies. On the other hand, the metallicity of our less massive galaxies \((10^{9.95}\, M_{\odot} < M < 10^{10.48}\, M_{\odot})\) shows a slight enhancement from the MZR of Zahid et al. (2014). Importantly, our targets and the sample in Stott et al. (2013) are selected by NB (Hα) selection, while Zahid et al. (2014) select their sample by the \(K\)-band magnitude. The discrepancy between the two studies for field galaxies could be caused by their different sample selection, and thus we consider that it would be more appropriate to compare our results to Stott et al. (2013), who selected their spectroscopic sample from the NB (Hα) imaging data.

We then investigated the metallicity offset of our cluster sample from the FMR shown by Stott et al. (2013). We find that both of our MOIRCS subsamples and the LUCI low-mass sample are consistent with the FMR of Stott et al. (2013) within 1σ. The LUCI high-mass sample shows a slightly larger offset, but it is still within the 2σ level. We therefore conclude that our cluster galaxies have the gas-phase metallicity comparable to the field galaxies at similar redshifts. It should be noted that some previous studies show a lower, consistent, and higher metallicity in high-\(z\) clusters compared to field galaxies (e.g., Kulas et al. 2013; Kacprzak et al. 2015; Shimakaw et al. 2015; Tran et al. 2015; Valentin et al. 2015). The authors always try to introduce some preferable mechanisms to explain their results; e.g., higher recycling rate, enriched IGM, and pristine inflow, all of which are supported by the observations or simulations (e.g., Davé et al. 2008, 2011; Dekel et al. 2009; Torrey et al. 2012; Ellison et al. 2013). Continuous efforts for determining the MZR in high-\(z\) cluster environments are necessary to understand whether environment would ubiquitously affect the galaxy metallicity and, if the environment really matters, we need to understand what kind of process is at work.

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