Properties of star-forming galaxies in a cluster and its surrounding structure at $z = 1.46$

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ABSTRACT

We conduct a wide-field narrow-band imaging survey of [O II] emitters in and around the XMMXCS J2215.9−1738 cluster at $z = 1.46$ with Subaru/Suprime-Cam. In a $32 \times 23$ arcmin² area, we select 380 [O II] emitting galaxies down to $1.4 \times 10^{-17}$ erg s⁻¹ cm⁻². Among them, 16 [O II] emitters in the central region of the cluster are confirmed by near-infrared spectroscopy with Subaru/MOIRCS, suggesting that our photometric selection is valid for sample [O II] emitters at $z = 1.46$. We find that [O II] emitters are distributed along filamentary large-scale structures around the cluster, which are among the largest structures of star-forming galaxies ever identified at $1.3 \lesssim z \lesssim 3.0$. We define several environments such as cluster core, outskirts, filament and field in order to investigate the environment dependence of star-forming galaxies at $z = 1.46$. The colour–magnitude diagram of $z′ - K$ versus $K$ for the [O II] emitting galaxies shows that a significantly higher fraction of [O II] emitters with red $z′ - K$ colours is seen in the cluster core than in other environments. It seems that the environment that hosts such red star-forming galaxies shifts from the core region at $z = 1.46$ to the outskirts of clusters at lower redshifts. A multicolour analysis of the red emitters indicates that these galaxies are more like nearly passively evolving galaxies which host [O II] emitting active galactic nuclei (AGNs), rather than dust-reddened star-forming [O II] emitters. We argue therefore that AGN feedback may be one of the critical processes to quench star formation in massive galaxies in high-density regions. The emission line ratios of $[O \text{ III}]/H\beta$ and $[N \text{ II}]/H\alpha$ of the [O II] emitters in the cluster core suggest the inference that there is a moderate contribution of AGN to the emitters. We also find that the cluster has experienced high star formation activities at rates comparable to that in the field at $z = 1.46$ in contrast to lower redshift clusters, and that star formation activity in galaxy clusters on average increases with redshift up to $z = 1.46$. In addition, line ratios of $[N \text{ II}]/H\alpha$ and $[O \text{ III}]/H\beta$ indicate that a mass–metallicity relation exists in the cluster at $z = 1.46$, which is similar to that of star-forming galaxies in the field at $z \sim 2$. These results all suggest that at $z \sim 1.5$ star formation activity in the cluster core becomes as high as those in low-density environments and that there is apparently not yet a strong environmental dependence, except for the red emitters.

Key words: galaxies: clusters: general – galaxies: clusters: individual: XMMXCS J2215.9−1738 – galaxies: evolution.

1 INTRODUCTION

Recently, galaxy clusters at a high redshift of $z > 1$, especially $z \gtrsim 1.5$, are found one after another (Kurk et al. 2009; Henry et al. 2010; Papovich et al. 2010; Tanaka, Finoguenov & Ueda 2010; Fassbender et al. 2011; Gobat et al. 2011). These high-$z$ clusters provide important clues to understanding galaxy formation and evolution, since the redshift of $z > 1$ approaches the epoch when galaxy clusters were formed. The importance of $z \gtrsim 1$ for galaxy evolution is also supported by the fact that the cosmic star formation activity and the number density of active galactic nuclei...
(AGN) both come to a peak at $z = 1–3$ (e.g. Ueda et al. 2003; Hopkins & Beacom 2006), and this redshift range corresponds to the epoch in which galaxies and AGNs are evolving vigorously. In galaxy clusters at low and intermediate redshifts of $z < 1$, a prominent sequence of red galaxies is seen in a colour–magnitude diagram (e.g. Bower, Lucey & Ellis 1992; Kodama et al. 1998; Stanford, Eisenhardt & Dickinson 1998; van Dokkum et al. 1998; Blakeslee et al. 2003; Tanaka et al. 2005; De Lucia et al. 2007). It is also well known that clusters are dominated by early-type galaxies. On the other hand, in protoclusters at a high redshift of $z > 3$, overdense regions of star-forming galaxies such as Lyman $\alpha$ emitters and Lyman break galaxies are reported (e.g. Steidel et al. 1998). Kodama et al. (2007) found a deficit of massive galaxies on the red sequence in protoclusters at $z \sim 3$, while such red galaxies are already in place in protoclusters at $z \sim 2$ (see also Kajisawa et al. 2006; Kriek et al. 2008; Doherty et al. 2010). These results suggest that the blue star-forming galaxies in the early phase evolve into red passive galaxies in high-density regions during the redshift interval of 1–3. In fact, recent studies show that clusters at $z \gtrsim 1.5$ are having active star formation even in the core regions (Hayashi et al. 2010; Hilton et al. 2010; Papovich et al. 2010; Tran et al. 2010; Fassbender et al. 2011). It is thus important to reveal star formation and AGN activities in galaxy clusters at this epoch.

An effective method of selecting star-forming galaxies is to search for emission line galaxies based on narrow-band imaging, which enables us to sample star-forming galaxies with a line emission stronger than a certain limiting flux and an equivalent width. A wide-field imaging is also essential to cover cluster outskirts and the surrounding field regions as well as cluster cores for environmental studies. Recent studies have discovered that the medium-density regions on the outskirts of galaxy clusters are the key environment to determine galaxy properties such as colours and star formation activities during the course of cluster assembly (Tanaka et al. 2005; Koyama et al. 2008). They found that the colours of galaxies change sharply from blue to red in such medium-density regions. Furthermore, Koyama et al. (2008) found that it is possible that star formation is the most active in the medium-density regions at $z = 0.81$. These studies have demonstrated the importance of wide-field surveys comprehensively, covering the full range of environments from cluster cores to the surrounding fields.

Moreover, follow-up spectroscopy of the emitters detected in the narrow-band imaging is essential to characterize their detailed properties such as dust-corrected star formation rate (SFR), AGN contribution and gaseous metallicity. At $z = 1–3$, because all the useful emission lines such as H$\alpha$, H$\beta$ and [O II] are redshifted into the near-infrared regime, deep multi-object near-infrared (NIR) spectroscopy becomes critically important and effective. Dust correction is one of the major uncertainties in characterizing galaxy properties from the observed data, and the Balmer decrement measurement (H$\beta$/H$\alpha$) with NIR spectroscopy is essential to make accurate correction for dust extinction. Moreover, recent NIR spectroscopic observations of star-forming galaxies at high redshifts have revealed that there is a mass–metallicity relation up to $z \sim 3$, and that the chemical evolution is seen in the sense that galaxies with a given stellar mass have lower metallicities on average with increasing redshift (Maiolino et al. 2008; Mannucci et al. 2009). More recently, Mannucci et al. (2010) discovered a fundamental relationship between stellar mass, metallicity, and SFR, which indicates that galaxies with smaller stellar masses and/or higher SFRs have lower metallicities. It should be noted that metallicities of galaxies also depend on the sample selection (e.g. Hayashi et al. 2009; Onodera et al. 2010; Yoshikawa et al. 2010). All these previous studies were, however, conducted in general fields, and it is yet unknown whether such mass–metallicity relation is established in clusters and how it depends on environment. Metallicity of star-forming galaxies provides information on the integrated star formation history in galaxies and it is independent of the snap-shot measurement of on-going star formation rate at each epoch. Therefore, the NIR spectroscopy of star-forming galaxies in various environments at $z > 1$ is the key to understanding galaxy evolution and its environmental dependence in much greater detail.

We have been conducting deep and wide-field surveys of H$\alpha$ and [O II] emitters in some general fields and in galaxy clusters at various redshifts at $z > 0.4$ as MAHALO–Subaru project (MMapping HALpha and Lines of Oxygen with Subaru; PI is T. Kodama). Among the clusters targeted by our project, XMMXCS J2215.9–1738 cluster (hereafter XCS2215 cluster) at $z = 1.46$ (Stanford et al. 2006) is one of the most massive galaxy clusters at a high redshift of $z > 1$. Hayashi et al. (2010) reported a deep survey of [O II] emitters in the central $6 \times 6$ arcmin$^2$ region of the XCS2215 cluster, and found that there are a lot of star-forming galaxies even in the cluster core where almost no star formation is seen in lower-$z$ clusters. Hilton et al. (2010) found eight mid-infrared (24 $\mu$m) sources in the central region of the XCS2215 cluster with Spitzer/MIPS, which supports our results that a relatively large fraction of galaxies in the XCS2215 cluster are still having active star formation. The previous [O II] survey (Hayashi et al. 2010) was limited to the central $6 \times 6$ arcmin$^2$ area where we had the MOIRCS $K_s$-band data as well. In this paper, we expand our previous survey to the outskirts of this cluster in order to investigate the environmental dependence of galaxy properties at $z = 1.46$. Our new UKIRT wide-field $K$-band imaging data now enable us to perform the analysis over the full Suprime-Cam field across $\sim 30$ arcmin in diameter. At the same time we perform a follow-up NIR spectroscopy of the [O II] emitters identified in the central region of the cluster to examine their properties in detail.

The structure of this paper is as follows. Observations and available data for the XCS2215 cluster are described in Section 2. Then, [O II] emitters at $z = 1.46$ around the cluster are selected from the photometric catalogues in Section 3. Some of the [O II] emitters are confirmed by spectroscopy in Section 4. In Section 5, environmental dependence of colour, SFR and specific SFR are discussed, and we compare the star-forming activity of this cluster to those of lower-$z$ clusters in Section 6. In Section 7, we investigate AGN contribution, dust extinction and gas-phase metallicity based on the emission line ratios between H$\alpha$, H$\beta$, [O II] and [N II] lines. Finally, in Section 8, we summarize the results of this paper and make our conclusions. Throughout this paper, magnitudes are presented in the AB system, and we adopt cosmological parameters of $h = 0.7$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. Vega magnitudes in $J$ and $K$, if preferred, can be obtained from our AB magnitudes using the relations: $J'(\text{Vega}) = J(\text{AB}) − 0.92$ and $K'(\text{Vega}) = K(\text{AB}) − 1.90$, respectively. In $z = 1.46$, 1 arcmin corresponds to 1.25 Mpc (comoving) and 0.51 Mpc (physical), respectively.

### 2 OBSERVATIONS AND DATA

#### 2.1 Optical imaging data

We have obtained optical imaging data of the XCS2215 cluster with Subaru Prime Focus Camera (Suprime-Cam; Miyazaki et al. 2002) on the Subaru telescope. Suprime-Cam consists of 10 2048 × 4096 CCDs with a pixel scale of 0.20 arcsec, and has a wide field-of-view (FoV) of $34 \times 27$ arcmin$^2$, which enables us to cover from the
central region to the outskirts of the cluster by a single pointing. Our multiwavelength data set consists of four broad-band images in $B$, $R_c$, $i'$, $z'$ bands, and a narrow-band image of NB912 ($\lambda_c = 9139$ Å, $\Delta \lambda = 134$ Å).

The observations were conducted in two semesters. The $B$, $z'$- and NB912-band imaging were performed under a normal open-use programme (S08A-011, PI: T. Kodama) on 2008 July 30–31, while $R_c$- and $i'$-band imaging were performed under a service-mode open-use programme (S09A-168S, PI: M. Hayashi) on 2009 July 20. The details of the observation and data reduction for $B$, $z'$ and NB912 data are presented in Hayashi et al. (2010). In this paper, therefore, we mainly describe the additional data in $R_c$ and $i'$. The individual exposure times of a frame in $R_c$ and $i'$ were 8 and 6 min, and the total integration times were 88 and 90 min, respectively. The weather was fine during the observations. The sky condition was mostly photometric, although thin cirrus occasionally passed the targeted location. The seeing was 0.6–0.8 arcsec in both $R_c$ and $i'$.

The data reduction of $R_c$ and $i'$ was carried out in the same manner as for the $B$, $z'$ and NB912 data, and we used the data reduction package for Suprime-Cam (SDFRED ver.1.4; Yagi et al. 2002; Ouchi et al. 2004). The point spread functions (PSFs) in the $R_c$ and $i'$ images were matched to 1.09 arcsec, which was the PSF size of the other optical data. The photometric zero-points were determined using the photometric standard stars in SA113 (Landolt 1992). The 3$\sigma$ limiting magnitudes were 27.1 and 26.8 in $R_c$ and $i'$, respectively. The specifications of all the optical data are summarized in Table 1.

### Table 1. Summary of the optical and NIR imaging data. The limiting magnitudes are measured with a 2-arcsec diameter aperture. Note that the $J$-band data are available only in the central region of the cluster, and its depth depends on the position due to non-uniform integration times. The PSFs in all the co-added images are matched to 1.09 arcsec.

| Filter | Effective area (arcmin$^2$) | Net integration (min) | Limiting mag. (3$\sigma$) | Instrument | Observation date |
|--------|-----------------------------|-----------------------|--------------------------|------------|------------------|
| $B$    | $32 \times 23$              | 140                   | 27.6                     | Subaru/Suprime-Cam | 2008 July 30–31$^\dagger$ |
| $R_c$  | $32 \times 23$              | 88                    | 27.1                     | Subaru/Suprime-Cam | 2009 July 20    |
| $i'$   | $32 \times 23$              | 90                    | 26.8                     | Subaru/Suprime-Cam | 2009 July 20    |
| $z'$   | $32 \times 23$              | 80                    | 25.8                     | Subaru/Suprime-Cam | 2008 July 30–31$^\dagger$ |
| NB912  | $32 \times 23$              | 260                   | 25.8                     | Subaru/Suprime-Cam | 2008 July 30–31$^\dagger$ |
| $J$    | $6 \times 6$                | 32.5–92.3             | 23.8–24.6                | Subaru/MOIRCS   | 2007 August 07$^\dagger$, 2008 June 29–30$^\dagger$ |
| $K$    | $23 \times 23$              | 123                   | 23.4                     | UKIRT/WFCAM     | 2010 July 30–31 |

$^\dagger$ Hayashi et al. (2010); $^\ddagger$ Hilton et al. (2009).

2.2 Near-infrared imaging data

The NIR imaging data are updated from Hayashi et al. (2010), where we had $J$- and $K_c$-band data covering only the central 6 $\times$ 6 arcmin$^2$ region with Multi-Object Infrared Camera and Spectrograph (MOIRCS; Ichikawa et al. 2006; Suzuki et al. 2008) on the Subaru telescope. MOIRCS consists of two 2048 $\times$ 2048 HgCdTe detectors with a pixel scale of 0.117 arcsec, and its FoV is 4 $\times$ 7 arcmin$^2$.

We have now obtained a new wide-field $K$-band data with Wide Field Camera (WFCAM; Casali et al. 2007) on the United Kingdom Infrared Telescope (UKIRT) on 2010 July 30–31 (U/10A/J3, PI: Y. Koyama) in order to cover the entire region of the optical data. WFCAM consists of four 2048 $\times$ 2048 HgCdTe detectors with a pixel scale of 0.4 arcsec, and each detector can cover 13.65 $\times$ 13.65 arcmin$^2$ region. Because the detectors are spaced with a gap of 12.83 arcmin, four pointings are required to get a contiguous sky coverage of 0.75 deg$^2$. A dither pattern of five points with 2 $\times$ 2 small microstepping was set for each pointing, and so the individual exposures were conducted at 20 different positions for a cycle at each pointing. The exposure time of each frame was 10 s, and the total integration time at each pointing was 123 min. The weather was fine throughout the two days of the observing run, and the sky condition was photometric. The seeing was ~1.0 arcsec.

We reduced the WFCAM data in a standard manner using our own IRAF-based software (provided by K. Motohara). First, we subtracted a dark frame from individual object frames, and then a self-flat image was created by combining 80 frames (four cycles) and taking a median value at each pixel. After flat-fielding, all the object frames were temporarily mosaicked and co-added. We then conducted a source detection on the co-added image. Next, after masking the detected objects in the individual frames, we make self-flat images again, and then conduct a flat-fielding per each observation cycle of 20 frames. After the sky background was subtracted from each frame, 20 frames of each cycle are combined. Finally, PSF sizes of the images of each cycle are matched, and the frames were mosaicked and co-added to make the final images. Special care was taken to exclude spurious objects resulting from the cross-talk of bright objects. PSF in $K$ was matched to 1.09 arcsec. The photometric zero-point was determined with 2MASS catalogue (Skrutskie et al. 2006). The 3$\sigma$ limiting magnitude was 23.3 in $K$. The specifications of the NIR data are also summarized in Table 1.

For $J$ band, we added the archival data with MOIRCS by Hilton et al. (2009) to our own data. Hilton et al. (2009) observed a 4 $\times$ 4 arcmin$^2$ region of the central region of the cluster with the chip 2 only of MOIRCS with an exposure time of 1485 s in total. Combining the archive data with our own data, we conducted the data reduction again in the same manner as in Hayashi et al. (2010) using the data reduction package for MOIRCS (MCSRED$^\dagger$ by I. Tanaka et al.). PSF in $J$ was matched to 1.09 arcsec.

2.3 Near-infrared spectroscopic data

We conducted a follow-up NIR spectroscopy of [O II] emitters in the central region of the cluster with MOIRCS on the Subaru telescope on 2009 September 3–7 (S09B-012, PI: T. Kodama). For 34 out of 44 [O II] emitter candidates identified in Hayashi et al. (2010), we obtained NIR low-resolution spectra with $z$/500 grism with a resolution of $R = 700$ at $J$ band and a wavelength coverage of 0.9–1.8 $\mu$m. The dispersion was 5.57 $\AA$ pixel$^{-1}$. We used two masks, and 17 slits were allocated to the [O II] emitter candidates in each mask.

$^\dagger$ http://www.naoj.org/staff/ichi/MCSRED/mcsred.html
Table 2. Summary of the spectroscopic observations with Subaru/MOIRCS.

| Slitmask | # of target | Grism | Integration (min) | Seeing (arcsec) |
|----------|-------------|-------|-------------------|-----------------|
| MOS1     | 17          | ∞J500 | 180               | 0.55–0.80       |
| MOS2     | 17          | ∞J500 | 300               | 0.45–0.60       |

The width and the length of individual slits were 0.7 arcsec and 11–12 arcsec, respectively. Depending on the positions of slits on the mask, 24 spectra have a wavelength coverage of 1.0–1.7 μm, which can neatly cover all the redshifted Hα, Hβ, [O III] and [N II] emission lines if present. The remaining 10 spectra have a coverage of 1.0–1.35 μm, which covers Hβ, and [O III] emission lines. Moreover, about two-thirds of the spectra, i.e. 21 [O II] emitters, extend down to 0.9 μm. The specifications of the spectroscopic observations are summarized in Table 2.

We observed the targets consecutively at two positions (A and B) with an offset of 3 arcsec on the slit. A single exposure time was 600 or 900 s depending on the sky background level. The total on-source integration time was 3 h for the MOS1 mask and 5 h for the MOS2 mask. We also observed a standard star BD+17°4708 (Bohlin & Gilliland 2004) on each night to correct for a telluric absorption as well as the instrumental efficiency, and to make flux calibration. Most of the time during the observations, however, the weather condition was not good and the sky was covered with thin cirrus and not photometric. Therefore, the absolute flux calibration was very difficult for these spectra. The seeing was 0.45–0.80 arcsec in FWHM.

The data reduction was done with standard procedures using IRAF. First, bad pixels and cosmic rays were removed from each frame, and a A–B frame was created from a pair of successive frames observed at the two positions A and B. Then, flat-fielding was done with a dome-flat image for the individual A–B images. Next, distortion was corrected using a calibration data provided by the MOIRCS instrument team. After extracting a spectrum at each slit, wavelength calibration was done with the OH airglow lines. Then, residual sky subtraction was carried out, since the A–B procedure alone might not completely remove the sky background due to its time variation. All the spectra for each [O II] emitter were then co-added and a one-dimensional spectrum was extracted by combining 10 pixels along a slit. Finally, the telluric absorption and the instrumental efficiency were corrected using the spectra of BD+17°4708. As an error, the sky noise was estimated as a square root of the photon count on the sky spectrum.

2.4 Photometric catalogue

We make a photometric catalogue in the same manner as in Hayashi et al. (2010), but for the wide-field 32 × 23 arcmin² data instead of the central 6 × 6 arcmin² region of the cluster. In this section, we briefly describe our updated photometric catalogue.

Source detections are performed on the NB912 image using SExtractor (ver. 2.5.0: Bertin & Arnouts 1996), and photometry on the other images, except for the J band, are conducted by the double-image mode of SExtractor. Because the FoV of the J-band image is limited to the central region and the pixel scale of MOIRCS image is smaller than that of Suprime-Cam, the J image is not matched to the NB912 image geometrically. Therefore, we independently conduct source detections and photometry on the J image with SExtractor, and cross-match the detected objects to those in the NB912-detected catalogue if the coordinates of the J-detected objects are in agreement with those of the NB912-detected objects within a 1-arcsec-diameter circle. Colour indices are derived from the 2-arcsec-diameter aperture magnitudes, and Mmag, AUTO magnitudes are used as total magnitudes. Magnitude errors are estimated from 1σ sky noise taking account of the difference in depth at each object position due to slightly different exposure times and sensitivities. Magnitudes are corrected for the Galactic absorption by the following magnitudes: A(B) = 0.10, A(R) = 0.06, A(‘) = 0.05, A(‘’) = 0.04, A(NB912) = 0.04, A(J) = 0.02 and A(K) = 0.01, which are derived from the extinction law of Cardelli, Clayton & Mathis (1989) on the assumption of Rv = 3.1 and E(B−V) = 0.025 estimated from Schlegel, Finkbeiner & Davis (1998). We check the zero-points of magnitudes in all the bands by comparing stellar colours with those of stellar spectrophotometric atlas of Gunn & Stryker (1983). The zero-point magnitudes are corrected so that stellar colours are in good agreement with those of the stellar atlas. Note that the correction is smaller than 0.15 mag at most.

As a result, the catalogue contains 31 144 objects brighter than 25.20 mag in NB912 (5σ limiting magnitude) over the whole 32 × 23 arcmin² region, except for the masked regions. Among them, 27 430 galaxies are distinguished from 3714 stars based on B − z’ and z’ − K colours. This technique was devised by Daddi et al. (2004), and stars are actually well separated from galaxies on this colour–colour diagram (B − z’ versus z’ − K) (Daddi et al. 2004; Kong et al. 2006).

3 SELECTION OF [O II] EMITTERS

We already surveyed [O II] emitters in the central region of the XCS2215 cluster at z = 1.46 with a combination of NB912 and z’ bands, and identified 44 [O II] emitters (Hayashi et al. 2010). In this paper, we have expanded the survey area to the outskirts of the cluster applying the same technique as used in Hayashi et al. (2010). We thus only present a summary of our selection method below.

First, we select galaxies with an emission line at ~9139 Å by applying the following criteria:

(i) \[ z’ - NB912 \gtrsim -2.5 \log(1 - \sigma^2_{3\sigma, d} + \sigma^2_{3\sigma, NB912}/\sigma^2_d), \]
(ii) \[ z’ - NB912 \gtrsim -0.2, \]

where \( f_{3\sigma} \) is the 3σ sky noise flux in each band and \( f_{d} \) is the z’-band flux (Fig. 1). The first criterion is intended to select galaxies with an excess of \( z’ - NB912 \) colour redder than the 3σ photometric error. This corresponds to a line flux larger than \( 1.4 \times 10^{-17} \text{erg s}^{-1} \text{cm}^{-2} \). If the excess is due to a [O II] emission line at z = 1.46, the limiting flux corresponds to a dust-free SFR of 2.6 M⊙ yr⁻¹ according to the [O II]–SFR calibration in Kennicutt (1998). The second criterion corresponds to the observed equivalent width larger than 35 Å, which can exclude the possible contamination of galaxies due mainly to photometric errors. As discussed in Hayashi et al. (2010), the colour term in \( z’ - NB912 \) is negligible. As a result, we select 721 NB912 emitters from 27 430 galaxies over a ~700 arcmin² area (Fig. 1). Among them, 482 emitters are detected in K at more than 2σ level. In what follows, we deal with the K-detected emitters, because we identify the [O II] emitters based on their B − z’ and z’ − K colours. This means that our emitter sample is both flux- and mass-limited.

It is possible that the detected emission lines are any of the following major strong lines: Hα at z = 0.39, [O III] at z = 0.82–0.84, Hβ at z = 0.88 and [O II] at z = 1.46. Note that we find no
candidates for Lyα emitters at $z = 6.51$ in our sample, because our 482 NB912 emitters are all detected in $i'$ band. In order to discriminate [O II] emitters from other lines at different redshifts, we apply the colour selection criteria to the NB912 emitters:

$$\left( z'_{\text{cont}} - K \right) > (B - z'_{\text{cont}}) - 0.46 \cup \left( z'_{\text{cont}} - K \right) > 2.2,$$

where $z'_{\text{cont}}$ corresponds to a continuum flux calculated from equation (3) in Section 5.3. The original idea comes from Daddi et al. (2004) who devised the $BzK$ colour selection technique which can efficiently take out galaxies located in $1.4 < z < 2.5$. We modified the original selection boundaries in Hayashi et al. (2010) so that we can sample galaxies at $z = 1.46$ more completely. Note that the selection criteria (1) used in this paper are yet slightly different from those adopted in Hayashi et al. (2010). First, we use $z'_{\text{cont}}$ instead of $z'$, which enables us to remove a contribution of emission line to the continuum colour to be used in the colour selection. The other is that we use $K$ magnitudes taken with WFCAM/UKIRT instead of $K_s$ magnitude with MOIRCS/Subaru. We estimate $K_s(\text{MOIRCS}) = K(\text{WFCAM})$ colours using spectral templates of Coleman, Wu & Weedman (1980) which are redshifted to 1.46, and find that the difference between the filters can result in $K_s(\text{MOIRCS}) = K(\text{WFCAM}) = 0.02–0.05$. This works in the sense that the emitters close to the border tend to meet the criteria more easily.

With the above criteria, we select 376 [O II] emitters in total (Fig. 2a). In Hayashi et al. (2010), we identified 44 [O II] emitters in the central region of the cluster. We check whether this previous sample of [O II] emitters is reproduced in the current sample in this paper. Among the 44 [O II] emitters, however, 11 objects are not identified as [O II] emitters in the current sample. This is because of the update of photometric catalogue in particular in the $K$ band. The MOIRCS $K_s$ image used in Hayashi et al. (2010) is $0.3$ mag deeper than the WFCAM $K$ image, and we miss some [O II] emitters with faint $K$ magnitudes. In fact, seven objects out of 11 are not detected in the WFCAM $K$ imaging. However, for a uniformity of the data across the entire field, we use the WFCAM data in this paper. Hilton et al. (2010) have spectroscopically confirmed 44 member galaxies in the XCS2215 cluster. We have also confirmed membership for 16 [O II] emitters with spectroscopy (see Section 4). Among them, four NB912 emitters do not meet our [O II] selection criteria but they turn out to be real members at $z \sim 1.46$. We thus add them to our [O II] emitter sample. Consequently, our final [O II] emitter sample consists of 380 galaxies.

Ly et al. (2007) have classified emission line galaxies using only the optical colours. We test this selection method based on $R_c - i'$ versus $B - R_c$ and $i' - z'$ versus $R_c - i'$ diagrams used in Ly...
et al. (2007) and check whether it is effective in picking out [O\textsc{ii}] emitters at $z \sim 1.46$. If this classification works, we could select [O\textsc{ii}] emitters among those faint in $K$ magnitude, i.e. less massive star-forming galaxies. Fig. 2(b) shows $i' - z'$ and $R_\alpha - i'$ colours for [O\textsc{ii}] and the other NB912 emitters identified by the $Bz'K$ selection method, where H\textalpha{} emitters at $z = 0.39$ have already been excluded from the NB912 emitter sample based on the $R_\alpha - i'$ versus $B - R_\alpha$ colours (Ly et al. 2007). In Fig. 2(b), it seems that [O\textsc{ii}] emitters and the spectroscopically confirmed members are relatively well distinguished and confined mostly in the bottom-right side of the diagram (Ly et al. 2007). However, we also note that there are many contaminations from other lines at different redshifts. This suggests that the NIR data are essential to photometrically select galaxies at $z \sim 1$--2, and we decide not to use the optical colour selection.

Also, we calculate photometric redshifts using the \textit{EAZY} code (Brammer, van Dokkum & Coppi 2008) with six SED templates of \textit{EAZY\_v1.0} and based on the photometry in $B, R_\alpha, i', z'$ and $K$ bands for the $K$-detected subsample of spectroscopic members. However, 20 per cent of the spectroscopic members have completely wrong photometric redshifts at $z_{\text{phot}} < 1$. Therefore we do not use the photometric redshift technique either.

Therefore, in this paper, we will rely on the $Bz'K$ colour selection in identifying the [O\textsc{ii}] emitters at $z \sim 1.46$ among the NB912 emitters.

Fig. 3 shows the distribution of [O\textsc{ii}] emitters at $z \sim 1.46$, where grey regions are masked due to the bad quality of the image. We confirm that many [O\textsc{ii}] emitters exist in the central region, as is already reported in Hayashi et al. (2010). Moreover, due to the extension of our survey to the outskirts of the XCS2215 cluster, we also find that there is a prominent filamentary large-scale structure of [O\textsc{ii}] emitters from the east to the south of the cluster (Fig. 3). This filament is surely one of the largest structures of star-forming galaxies at $z = 1.46$. Recent studies suggest that at lower redshifts medium-density regions embedded in large-scale structures surrounding clusters are crucial sites to understand galaxy evolution (Tanaka et al. 2005; Koyama et al. 2008). The discovery of the large-scale structure at $z = 1.46$ provides us with a unique opportunity to investigate environmental dependence of galaxy properties, in particular those in such interesting medium-density environments at this high redshift. In Section 5, we examine the properties of galaxies in the filamentary structure, and compare them with those in different environments.

### 4 Spectroscopic Confirmation of the [O\textsc{ii}] Emitters

In Hayashi et al. (2010) and the previous section, we photometrically identify 380 [O\textsc{ii}] emitters at $z = 1.46$ in the XCS2215 cluster and its outskirts. However, the confirmation of [O\textsc{ii}] emitters by spectroscopy is essential to verifying that our method is valid for the selection of [O\textsc{ii}] emitters at $z = 1.46$.

By our MOIRCS spectroscopy, we have detected some emission lines, such as H\textalpha{}, H\beta{}, [O\textsc{iii}], [N\textsc{ii}], for 16 out of the 34 targeted [O\textsc{ii}] emitters in the cluster region. In the case of narrow-band emitters, it is relatively easy to identify the detected emission line even if only a single line is detected on the spectrum. Because we already detect an emission line at $\sim 9139$ Å by narrow-band imaging, the possible redshifts of the emitters are very limited. For [O\textsc{ii}] emitters at $z = 1.46$, H\textalpha{} and [N\textsc{ii}] lines should be seen at $\lambda \sim 1.61$ µm, while H\beta{} and [O\textsc{ii}] lines should be seen at $\lambda \sim 1.19$ and 1.23 µm, respectively.

We first perform line detections in the two-dimensional spectra by visual inspection, taking care not to be confused by residual OH airglow lines or any accidental noises. Among the confirmed lines,

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**Figure 3.** The celestial distribution of our 380 [O\textsc{ii}] emitters at $z \sim 1.46$ in and around the XCS2215 cluster. North is up, and east is to the left. The horizontal and vertical axes show relative coordinates from the cluster centre. Black dots show the [O\textsc{ii}] emitters, and grey regions indicate the masked areas around bright stars which have bad quality image and were excluded from the analyses. Cluster core region is defined by a dotted-line circle with a radius of 2 arcmin, while the outskirts region is defined as a ring with a width of 2 arcmin between the dotted and broken-line circles. Filament region shown by the long-dashed lines and is defined to cover the prominent structure of the [O\textsc{ii}] emitters. The rest of the area is defined as the field. Blue, magenta and green contours show the local density of $\log \Sigma_{\text{206}} [\text{Mpc}^{-2}] = 1.07, 0.72$ and 0.39, respectively (see Section 5.1).
we then regard a line with a flux larger than 2σ of the sky noise as a real signal. Figs 4 and 5 show the one-dimensional spectra of the lines, and a summary of the detected lines for the 16 confirmed [O II] emitters is presented in Table 3.

The spectroscopic redshifts and the fluxes of the emission lines are measured by fitting Gaussian profiles, where the free parameters are amplitude, linewidth and redshift. Before fitting, we estimate a constant continuum level using the regions close to the line and without a contribution of strong OH lines, and subtract it from each spectrum. The 1σ error of the spectrum is estimated from the covariance of χ² fitting based on the sky noise. We confirm that the error is comparable to the sum of the sky noise within...
2 × FWHM around each line. If a [N II] emission line is seen in a spectrum, Hα and a doublet of [N II] (λλ6548, 6584) are simultaneously fit to the spectrum, assuming the same linewidt and redshift, and a [N II](λ6584)/[N II](λ6548) ratio of 3. In the case where several lines are detected for an emitter, we determine its redshift by taking an average of the redshifts measured by individual lines.

As a result, we confirm that 16 [O II] emitters are certainly cluster member galaxies at z ∼ 1.46, which is nearly 50 per cent (16/34) of our [O II] emitter sample. For the other three targets, we do see an emission line at z ∼ 0.10, but it is the only detected line and we are not sure whether it is an [O II] line. The spectra of two of them do not cover the wavelength where Hα line should be seen, unfortunately. It is also possible that the detection limit of Hα at ∼1.61 μm is shallower than that of [O II] at ∼0.91 μm. For the remaining 15 targets, no emission line is detected even if a spectrum covers the wavelength range down to 0.9 μm. In the MOS1 (MOS2) mask, emission lines are detected for targets with [O II] fluxes larger than 0.41(0.23) × 10^{-16} erg s^{-1} cm^{-2} (see Table 4). We find that 12 out of the 15 targets without line detection have estimated [O II] fluxes similar to or smaller than the limiting flux. For the two targets with estimated [O II] fluxes large enough to be detected, their spectra do not cover the wavelength range down to 0.9 μm and we cannot confirm their [O II] emission lines. They do cover, however, the wavelength range up to 1.7 μm where Hα lines are expected to show up. But we do not detect them, either. For the remaining one target, although we obtain its spectrum covering 0.9–1.35 μm, no line is detected.
Figure 6. Redshift distributions of the cluster member galaxies. The blue histogram shows the 16 [O\textsc{ii}] emitters which are spectroscopically confirmed by our MOIRCS observations, while the black histogram shows all the 56 members of which 40 redshifts are taken from Hilton et al. (2010). Among the 44 members in Hilton et al. (2010), four objects overlap with our [O\textsc{ii}] emitters that are spectroscopically confirmed with MOIRCS. The solid curve shows the response function of the NB912 filter in an arbitrary unit.

Therefore, except for the three targets with strong enough estimated [O\textsc{ii}] fluxes, non-detection of any emission lines for the [O\textsc{ii}] emitter candidates are probably because of intrinsically too weak [O\textsc{ii}] emission lines, as well as other lines which are also weaker than the detection limit. Non-photometric weather conditions during our spectroscopy may have resulted in the poor success rate of line detections.

Fig. 6 shows the redshift distribution of the confirmed [O\textsc{ii}] emitters and that of all the cluster members. We cross-identify our 16 [O\textsc{ii}] emitters to the 44 member galaxies in Hilton et al. (2010), and four galaxies turn out to be common objects whose coordinates match to an accuracy of 1 arcsec. Hilton et al. (2010) suggest that the redshift distribution may have double peaks, and that such a profile may indicate that this cluster experienced a cluster–cluster merger event within the past few Gyr. A similar double-peaked profile is also seen for the [O\textsc{ii}] emitters as well as all the member galaxies (Fig. 6). Although Hayashi et al. (2010) found a high fraction of [O\textsc{ii}] emitters in the core region of the XCS2215 cluster, we were not able to reject the possibility that it is due to a projection effect of the [O\textsc{ii}] emitters on the outskirts along the line of sight which are apparently superposed on to the cluster core. However, similarity in the redshift distributions between the [O\textsc{ii}] emitters and all the member galaxies (Fig. 6) strongly suggests that the emitters are indeed located in the cluster core in space.

5 ENVIRONMENTAL DEPENDENCE

5.1 Definition of environments

We define four different environments (core, outskirts, filament and the field) based on the spatial distribution of [O\textsc{ii}] emitters as shown in Fig. 3. The core is defined as a circled region with a radius of 2 arcmin from the cluster centre, while the outskirts are defined as a ring with an inner radius of 2 arcmin and an outer radius of 4 arcmin. The filament is defined as an area enclosed by the long-dashed lines that neatly cover the notable filamentary structure characterized by the relatively high density of the [O\textsc{ii}] emitters. All of the rest is defined as the field region.

As another definition of environment, we will also use local density \( \Sigma_{5\text{th}} \), which is calculated using the area where the fifth nearest [O\textsc{ii}] emitters are included. In the local density measurements, it would be desirable to use a whole sample of \( z = 1.46 \) galaxies including not only blue star-forming galaxies but also red quiescent galaxies. However, the current photometric redshifts (without \( J \) band in particular) are not accurate enough to define such local density of the whole population. Therefore, we count only the [O\textsc{ii}] emitters to define local density as they are most likely located at \( z = 1.46 \) with little contamination from foreground or background galaxies. It should be noted that Hayashi et al. (2010) found that the fraction of [O\textsc{ii}] emitters in this cluster is almost constant irrespective of the distance from the cluster centre. This suggests that even if only [O\textsc{ii}] emitters are used to calculate the local density, we can expect to trace the structure of the whole population to some extent.

Fig. 7 shows the distribution of the local density \( \Sigma_{5\text{th}} \) of the [O\textsc{ii}] emitters in each environment defined above based on Fig. 3. If the four environments are rearranged in the order of decreasing local density, the core is the highest density region, the filament is the second, the outskirts are the third and the field is the lowest density regions. Note that the large-scale filamentary structure (i.e. filament) is actually denser than the cluster outer region (i.e. outskirts).

When we discuss environmental dependence of galaxy properties below based on the local density, we divide the galaxies into four classes according to the local densities, each of which contains an equal number of [O\textsc{ii}] emitters (~95). The boundaries between the classes are shown by the two vertical dotted lines in Fig. 7.

5.2 colour–magnitude diagram

Fig. 8 shows the colour–magnitude diagrams in each environment. In the left-hand panel the four environments are defined based on the spatial distribution of the [O\textsc{ii}] emitters, while in the right-hand panel the four environments are divided based on the local density (see Section 5.1). The distribution of the [O\textsc{ii}] emitters on
the colour–magnitude diagrams indicates that the [O\text{II}] emitters seem to be blue galaxies in general as expected. However, there are some red [O\text{II}] emitters with $z' - K > 2.2$. The fraction of the red [O\text{II}] emitters seems higher in high-density regions, such as core, filament and high-$\Sigma_{\text{th}}$ regions, compared to other environments.

Fig. 9 shows this trend quantitatively. The fraction of the red [O\text{II}] emitters ($z' - K > 2.2$) to all the [O\text{II}] emitters is plotted as a function of environment. The galaxies redder than $z' - K = 2.2$ can be called ‘red-sequence’ galaxies for the cluster redshift at $z = 1.46$ (Hayashi et al. 2010). The figure clearly shows an excess of red [O\text{II}] emitters towards high(est) density regions. Koyama et al. (2010) reported that such red star-forming galaxies in the RXJ1716.8+6708 cluster at $z = 0.81$ are preferentially seen in high-density regions, such as groups, filaments and the outskirts of the cluster, rather than in the high-density cluster core. They claim that it indicates that the cluster at $z = 0.81$ has already quenched the star formation activity in the high-density region, and the region of active star formation has been shifted to the medium-density regions. Tanaka et al. (2009) also found that there are a few red galaxies with [O\text{II}] emission in the RDCS J1252.9–2927 cluster at $z = 1.24$, and such galaxies tend to exist in groups or in the field. These facts may suggest that the central region of the cluster at $z = 1.46$ is at a stage of galaxy evolution similar to that of the outskirts of clusters at lower redshifts, where red star-forming galaxies appear.

It is clear from Fig. 8, that the colour and magnitude of the [O\text{II}] emitters correlate in the sense that brighter emitters in $K$ tend to be redder in $z' - K$. Furthermore, in this cluster, the colour–magnitude diagram shows a deficit of red-sequence galaxies with $K$ fainter than $z' - K > 21.5$ (Hayashi et al. 2010). Galaxy properties are thus strongly magnitude-dependent. We therefore investigate the dependence of the fraction of red [O\text{II}] emitters on the $K$-band luminosity. It is found that the higher fraction of red [O\text{II}] emitters towards high-density regions is dominated by massive [O\text{II}] emitters with $K < 21.5$ (Fig. 9). For less massive [O\text{II}] emitters with $K > 21.5$, the fraction of red [O\text{II}] emitters is very small, and is not strongly dependent on the environment. It is likely that massive [O\text{II}] emitters in high-density regions change to red colours earlier than the less massive ones and/or in lower density environments. This is consistent with the downsizing scenario that more massive galaxies become quiescent galaxies earlier, and with its
environmental dependence in the sense that galaxy evolution (and downsizing) proceeds earlier in higher density regions (e.g. Tanaka et al. 2005).

Fig. 10 shows the $J - K$ versus $z' - K$ colour–colour diagram for the 6 × 6 arcmin$^2$ region in the cluster centre where $J$-band photometry is available. We utilize this diagram to investigate the nature of the red [O ii] emitters. This method is analogous to the one that is used to separate starburst galaxies from passive galaxies for Extremely Red Objects (EROs) based on the strength of the Balmer/4000 Å break feature (e.g. Pozzetti & Mannucci 2000). In the XCS2215 cluster, Hilton et al. (2010) found eight 24-μm sources with Spitzer/MIPS and three AGNs identified by Chandra X-ray data and Spitzer/IRAC mid-IR colours. Among them, we cross-identified seven dusty starbursts and three AGNs in our catalogue of cluster member candidates, and plotted them together in the figure. The arrow shows a reddening vector estimated from the extinction curve of Calzetti et al. (2000). The dashed line drawn in parallel to the reddening vector approximately separates between passive galaxies (upper) and dusty galaxies (lower). The dotted line shows the colour of $z' - K = 2.2$.

is caused by enhanced AGN activity in almost passively evolving galaxies.

Yan et al. (2006) found that [O ii] emission lines from red galaxies tend to be produced by AGN activities rather than star-forming activities in the local Universe. Lemaux et al. (2010) also found similar results at $z = 0.8$–0.9. These support our results. The high fraction of red [O ii] emitters in high-density regions may suggest that AGN feedback is contributing to quench star formation activities in galaxies. In fact, as we discuss in Section 7.1, the line ratio diagnosis indicates a moderate level of AGN contribution in the [O ii] emitters located in the central region of the XCS2215 cluster.

5.3 SFR, specific SFR and stellar mass

In this section, we derive SFRs and specific SFRs (SSFRs) of the [O ii] emitters from their [O ii] line fluxes (erg s$^{-1}$ cm$^{-2}$) and continuum flux densities (erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$). They are calculated from the flux densities in NB912 and $z'$ bands ($f_{\text{NB912}}$ and $f_{\text{z'}}$), respectively, as follows;

$$ F([\text{O} \text{ ii}]) = f_{\text{NB912}} \Delta_{\text{NB912}} 1 - \left( \frac{f_{\text{z'}}}{f_{\text{NB912}}} \right) \left( \frac{\Delta_{\text{NB912}}}{\Delta_{\text{z'}}} \right), $$  

$$ f_{\text{z',cont}} = f_{\text{z'}} \left( \frac{f_{\text{NB912}}}{f_{\text{z'}}} \right) \left( \frac{\Delta_{\text{NB912}}}{\Delta_{\text{z'}}} \right)^{-1}, $$

where $\Delta_{\text{NB912}}$ and $\Delta_{\text{z'}}$ indicate FWHMs of the filters, and $\Delta_{\text{NB912}} = 134$ Å and $\Delta_{\text{z'}} = 955$ Å.

The SFR is the fundamental quantity to characterize the star formation activity in a galaxy. We convert a [O ii] luminosity into an SFR using the calibration by Kennicutt (1998). For a dust extinction correction, we take the following empirical approach. Garn et al. (2010) have found a correlation between the observed Hα luminosity and the dust attenuation for Hα emitters at $z = 0.845$ under the High-z Emission Line Survey (HiZELS) (equation 6 in Garn et al. 2010):

$$ A_{\text{H} \alpha} = -19.46 + 0.50 \log_{10} \left( \frac{L_{\text{H} \alpha, \text{obs}}}{\text{erg s}^{-1}} \right). $$

Because the observed luminosity ratio between [O ii] and Hα is sensitive to dust extinction, the assumption of the constant $L_{\text{[O} \text{ii]}}/L_{\text{H} \alpha}$ is inadequate. Moustakas, Kennicutt & Tremonti (2006) have found that the correlation between the observed ratio of [O ii] to Hα and $E(B - V)$ is consistent with the Galactic extinction curve of O'Donnell (1994) for local star-forming galaxies, and we get

$$ \log_{10} \left( \frac{L_{\text{[O} \text{ii]}}}{L_{\text{H} \alpha}} \right)_{\text{obs}} = -0.861 \ E(B - V), $$

$$ = -0.342 \ A_{\text{H} \alpha}, $
Figure 11. SFRs of the [O II] emitters as a function of stellar mass in four environments: (a) core, (b) filament, (c) outskirts and (d) field. The left-hand panel shows the SFRs converted from the observed [O II] luminosities, while the right-hand panel shows the dust-corrected SFRs. See text for the details of the dust correction.

Figure 12. Same as Fig. 11, but for the specific SFRs.

For the [O II] emitters at $z = 1.46$, $K$ band corresponds to the rest-frame $z'$ band, i.e. $\sim 8900$ Å. We estimate stellar masses of the [O II] emitters using an empirical relation between stellar mass for $K$-selected galaxies at $z > 1.4$ and its $K$ magnitude given in Daddi et al. (2004). The mass-to-light ratio of a galaxy is calibrated with its $z - K$ colour, which can reduce the dispersion of derived stellar mass to $\sigma (\Delta \log (M_\odot)) = 0.20$ (Daddi et al. 2004). Using thus derived stellar mass of individual galaxies, we also derive SSFR by dividing SFR by the stellar mass.

Fig. 11 shows SFRs of the [O II] emitters in each environment as a function of stellar mass. There is a weak correlation that more massive galaxies tend to have larger SFRs, except for the [O II] emitters in the field region. It is also notable that, although there is a considerable scatter, for a given stellar mass, the [O II] emitters in the cluster have similar SFR to those of field galaxies at $z = 1.5$–2.5 (Erb et al. 2006b; Daddi et al. 2007; Hayashi et al. 2009; Yoshikawa et al. 2010). This suggests that, at $z = 1.46$ the environmental dependence of star formation activity is weak, and that galaxies in the XCS2215 cluster at $z = 1.46$ have conducted strong star formation activities just comparable to those in the general field.

Fig. 12 shows SSFR as a function of stellar mass, which suggests that more massive galaxies have lower SSFR. Massive galaxies do not necessarily enhance their star formation activity. We investigate the global SSFR, which are calculated from integrated SFR$_{corr}$ divided by integrated stellar mass for the [O II] emitters in each environment (Fig. 13). This figure also supports the inference that star formation activity of galaxies at $z = 1.46$ is not dependent on environment strongly.

At redshifts below unity or so, the star formation activity in clusters is significantly weaker than that in the surrounding regions. In RXJ1716.8+6708 cluster at $z = 0.81$ and XMMU J2235.3−2557 cluster at $z = 1.39$, no star-forming galaxies are found within
the redshift of \( z = 0.41 \) from Koyama et al. (2011); CL1040 (\( z = 0.794 \)) from Finn et al. (2005); RXJ1716 (\( M_M \sim \langle \Sigma \rangle_1 \)) from Couch et al. (2001); A2390 (\( M_M = \langle \Sigma \rangle_1 \)) from Balogh & Morris (2000); AC114 (\( M_M = \langle \Sigma \rangle_1 \)) from Balogh et al. (2002); A851 (\( M_M = \langle \Sigma \rangle_1 \)) from Kodama et al. (2004); A1237 cluster at \( z = 1.56 \). Most of the clusters at \( z > 1.5 \) are likely to hold active star formation in the core regions. In order to make an evolutionary link to the low-redshift clusters with inactive cores, some processes must take place to suppress star formation in the central regions in the short time interval between \( z \sim 1.5 \) and 1.0 (\( \gtrsim 1.5 \) Gyr).

### 6 Cosmic Evolution of Star Formation Activity in Clusters

In this section, we compare the global SSFR of the XCS2215 cluster with those of clusters at lower redshifts. For clusters at \( z < 1 \), the redshift evolution of the global SSFRs approximately follow a relation of \( \sim (1 + z)^b \) although the scatter is large (e.g. Finn et al. 2005; Koyama et al. 2010). For comparison with those previous studies, we derive integrated SSFR and dynamical mass of the XCS2215 cluster in the same manner as in the previous works.

To derive the integrated SFR (\( \Sigma SFR \)) in the XCS2215 cluster, we sum up individual SFRs of the [O\textsc{ii}] emitters within a radius of \( 0.5 \times R_{200} \), where \( R_{200} \) is a radius within which the averaged matter density is 200 times larger than the critical density. Previous studies apply a constant dust extinction, \( A_{HI} = 1 \), to derive intrinsic SFRs, which is different from our correction for dust extinction adopted in this paper. Thus, for this comparison only, we apply the same amount of correction, \( A_{HI} = 1 \). The cluster mass, \( M_M \), is estimated from the velocity dispersion of the cluster, which is 720 km s\(^{-1}\) (Hilton et al. 2010). Then, we use equations (4) and (5) of Koyama et al. (2010) to derive \( R_{200} \) and \( M_M \) for the XCS2215 cluster. The radius, \( R_{200} \), is 0.8 Mpc which corresponds to 1.57 arcmin (Hilton et al. 2010). The mass, \( M_M \), is \( 2.81 \times 10^{14} M_\odot \). As a result, the integrated SFR, \( \Sigma SFR \), is 764 \( \pm 23.3 M_\odot \) yr\(^{-1}\).

Before comparing with previous studies, there are two issues to be kept in mind. One is that \( R_{200} \) and \( M_M \) derived from the velocity dispersion may be overestimated. Hilton et al. (2010) pointed out that the redshift distribution of cluster members shows a bimodality, and thus this cluster may have been experiencing a merger event in the recent past within a few Gyr or so. Our spectroscopy also shows a similar redshift distribution for the [O\textsc{ii}] emitters. The other issue is that our [O\textsc{ii}] survey may be underestimating the integrated SFR compared to the \( H\alpha \) surveys. Our SSFRs are derived from [O\textsc{ii}] luminosities, while the SSFRs in the other studies are derived from \( H\alpha \) luminosities. Our [O\textsc{ii}] survey is probably more sensitive to dust extinction and the depth (2.6 \( M_\odot \) yr\(^{-1}\)) is also slightly shallower than the \( H\alpha \) surveys (<1 \( M_\odot \) yr\(^{-1}\)) at lower redshifts in terms of dust-free limiting star formation rates. In spite of such differences between our study and the previous ones, however, it is still worth comparing among these results.

Fig. 14 shows the SSFRs of clusters as a function of redshift. The XCS2215 cluster has the largest SSFR among the clusters plotted in the figure, and there is a general trend that the star formation activity in galaxy clusters increases with redshift out to \( z > 1.46 \). It should be noted that both of the two issues described above lead to the conservative estimation of SSFR for the XCS2215, which would therefore strengthen the trend that we claim. This result seems reasonable, because the cosmic star formation rate density keeps rising to \( z \sim 2 \) on average and the redshift of \( z = 1.46 \) is closer to the epoch when galaxy clusters are formed. Tadaki et al. (2011) suggest that the star formation activity in cluster/protocluster may be even stronger than in the field at \( z \sim 2 \). As suggested in Section 5,
the redshift range of $z = 1.5–2.5$ is probably the epoch when galaxies form stars very actively irrespective of their environments.

7 SPECTROSCOPIC PROPERTIES OF THE [O II] EMISSION LINES

In this section, we discuss spectroscopic properties of the [O II] emitters using the ratios of detected emission lines. Table 4 shows the observed [O II] luminosities and the ratios of emission lines.

7.1 AGN contribution

Since the AGN activity in the Universe peaks at $z \sim 2$ (e.g. Ueda et al. 2003), it is important to investigate a contribution of AGN to our [O II] emitters before discussing their spectroscopic properties. Yan et al. (2006) investigated the origin of [O II] emission lines from local galaxies using the SDSS data, and concluded that [O II] emission lines from red galaxies are dominated by radiation from low-ionization nuclear emission-line regions (LINERs), rather than star-forming H II regions. On the other hand, [O II] emission lines from blue galaxies mainly come from star formation. Lemaux et al. (2010) conducted NIR spectroscopy of LINER-type galaxies in clusters at $z = 0.8–0.9$ and obtained conclusions similar to those of Yan et al. (2006). Although most of our [O II] emitters have blue colours hence their [O II] emissions are likely due to star formation, these studies demonstrate the importance of evaluating the AGN contribution in our [O II] emitters.

The two emission line ratios of [N II]/Hα and [O II]/Hβ are frequently utilized to distinguish star-forming galaxies from AGNs (e.g. Baldwin, Phillips & Terlevich 1981; Kewley et al. 2001; Kauffmann et al. 2003). Fig. 15 shows a [N II]/Hα versus [O II]/Hβ diagram for our [O II] emitters in the XCS2215 cluster. The dashed line shows a boundary separating between star-forming galaxies and AGNs, which is defined based on the SDSS data (Kauffmann et al. 2003). The dotted line shows a theoretical boundary given by Kewley et al. (2001). For our spectroscopic sample, there are only three [O II] emitters with all the emission lines detected (see Table 3). If either of the line ratios is not available, we evaluate an upper or lower limit of the ratio by assuming a Gaussian profile with a peak flux that is twice the sky noise and $\sigma = 10 \AA$ for the non-detected line. We note that the assumed width of the Gaussian profile is comparable to those of the detected lines. We show the galaxies with such upper/lower limit(s) by open circles with arrow(s) in Fig. 15. Fig. 16 shows [N II]/Hα and [O II]/Hβ ratios, separately. The number of objects shown in the plots is significantly increased. The dot–dashed lines indicate Log([N II]/Hα) = −0.2 and Log([O II]/Hβ) = 0.83, respectively, above which emission line ratios are more AGN-like.

Almost all the [O II] emitters for which all the four emission lines are available are located in the composite region between the dotted and the broken lines in Fig. 15. Only one of them is clearly in the AGN region. Fig. 16 also shows that few [O II] emitters have a large contribution of AGN. Only three [O II] emitters are located above the threshold lines for AGN. Therefore, it is unlikely that our [O II] emitters are dominated by AGNs. Although the red [O II] emitters may have more contribution of LINER/Seyfert-type AGNs as pointed out by the previous studies (Yan et al. 2006; Lemaux et al. 2010), Fig. 8 shows that a large fraction of our [O II] emitters are distributed in the blue cloud, and thus most of the [O II] emission lines are more likely to be originating from star formation activity rather than AGN. At the same time, however, AGN contribution is not negligible, and a part of the [O II] emission line fluxes may come from AGNs.

Hilton et al. (2010) detected two X-ray point sources with Chandray among the spectroscopically confirmed members of XCS2215 cluster, whose limiting fluxes are $\approx 1.0 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2}$ corresponding to $L_{\text{X,2–10keV}} \gtrsim 0.8 \times 10^{42} \text{erg s}^{-1}$ at $z = 1.46$ if the spectral index of $\alpha = 2$ and $N_{\text{H}} = 1.0 \times 10^{22} \text{cm}^{-2}$ are assumed (Hilton et al. 2010). Moreover, they found that one of the 24-μm sources has a mid-infrared SED based on the Spitzer data that are consistent with an AGN although none of the 24-μm sources is detected in the X-ray data. Among these three AGN candidates, two (an X-ray source and a 24-μm source) are included in our [O II] emitter sample. The X-ray source is ID-2 of the [O II] emitters, while no line is detected in our MOIRCS spectrum for the 24-μm source. This suggests that most of our [O II] emitters are not heavily contaminated by AGN activities, except for the red [O II] emitters (Section 5.2 and Fig. 10).

All these results support the inference that the XCS2215 cluster has active star-forming activities even in the core of the cluster as reported in Hayashi et al. (2010) and Hilton et al. (2010). As Figs 15 and 16 indicate, we cannot completely ignore the contribution of AGNs, and in principle, we must take care of the influence of AGNs on the line flux when we discuss the properties based on the emission line fluxes. However, since it is impossible to quantitatively measure a contribution of AGN to the line flux with the currently
available data, we have to assume at this stage that [O II] fluxes originate purely from star formation in Section 5.3. It should be noted therefore that the SFRs derived from the [O II] luminosities are probably overestimated.

7.2 Dust extinction

The galaxy properties derived from the observables (colours and line intensities) are sensitive to the correction for dust extinction. In order to estimate the amount of dust extinction for stellar continuum flux, the SED fitting to the multiband photometric data is frequently conducted. However, it is hard to break the degeneracy between stellar age and dust reddening. Also, the amount of dust extinction for the nebular emission lines from H II regions is different from that of the stellar continuum SEDs. A large uncertainty exists in the conversion from stellar reddening to nebular reddening.

One of the reliable methods to derive the amount of dust extinction of the nebular emission is to use the Balmer decrement (i.e. Hα/Hβ ratio). Under the assumption of the Case B recombination, intrinsic flux ratio of the two Balmer lines is expected to be (Hα/Hβ)_{int} = 2.86. By comparing the observed flux ratio, (Hα/Hβ)_{obs}, with the intrinsic one, we can estimate the amount of dust extinction as follows:

\[ E(B-V) = \frac{2.5}{k(\lambda_{H\beta}) - k(\lambda_{H\alpha})} \log \left( \frac{(H\alpha/H\beta)_{int}}{(H\alpha/H\beta)_{obs}} \right), \]  

where \( k(\lambda_{H\beta}) - k(\lambda_{H\alpha}) = 1.14 \) as calculated from the O'Donnell (1994) extinction curve (as in Section 5.3).

There are four [O II] emitters in our spectroscopic sample for which both of the Balmer lines are detected. The derived amounts of dust extinction are \( E(B-V) = 0.543^{+0.355}_{-0.259} \), 0.910^{+0.397}_{-0.279} \), 0.401^{+0.197}_{-0.163} \), and 0.700^{+0.240}_{-0.192} for ID-7, ID-8, ID-10 and ID-15, respectively. These colour excesses correspond to \( A_{H\alpha} = 1.37^{+0.69}_{-0.52} \), 2.29^{+0.89}_{-0.70} \), 1.01^{+0.50}_{-0.41} \), and 1.76^{+0.69}_{-0.44}, respectively. Note that these \( E(B-V) \) values are comparable to those of the BzK-selected field galaxies (Yoshikawa et al. 2010). The estimated dust extinction is larger than the nominal value of Ha, \( A_{Ha} = 1 \), that is frequently used in the literature. If we correct [O II] fluxes only by the amount corresponding to \( A_{H\alpha} = 1 \) for all our emitters uniformly, the intrinsic [O II] fluxes are likely to be underestimated significantly.

For the two [O II] emitters of ID-6 and ID-8, both [O II] and Hα lines are detected. The observed ratio of the two lines can provide us with another estimation of \( A_{H\alpha} \) using equation (5). The observed ratios, \( L_{[O\ II]/L_{H\alpha}} \), for ID-6 and ID-8 [O II] emitters are 0.393 ± 0.217 and 0.438 ± 0.066, respectively. These correspond to \( A_{H\alpha} = 1.19^{+0.12}_{-0.06} \) and 1.05^{+0.22}_{-0.17}, respectively. For the ID-8, two independent measures of dust attenuation differ by a large amount (≈1 mag) although the uncertainties of both measurements are large. Such discrepancy may be caused by a contribution of an AGN to the line fluxes.

In Section 5, we use the dust extinction law which is dependent on SFR (i.e. Hα luminosity). Here, we can verify whether the Garn et al. (2010) relation is valid for our [O II] emitters using the spectroscopic sample. In the same manner as in Section 5, we estimate \( A_{H\alpha} \) from the [O II] flux derived from the narrow-band imaging but is corrected for filter response using the accurate spectroscopic redshift. We obtain \( A_{H\alpha} = 1.9-2.1 \) based on the Garn et al. (2010) relation, which is consistent with the estimated value by the Balmer decrement technique. Therefore our method of dust extinction correction based on the Garn et al. (2010) relation is confirmed to be valid for the [O II] emitters (Section 5). However, it is possible that [O II] fluxes are slightly overcorrected for dust extinction, and thus SFR_{corr} for the [O II] emitters may be a little overestimated.

7.3 Gas-phase metallicity

It is well known that the electron temperature reflects gas metallicity (Kewley & Dopita 2002; Kobulnicky & Kewley 2004; Erb et al. 2006a). Because the auroral lines which are used to derive electron temperature are weak and can be observed only for galaxies with low metallicities, it is very difficult to estimate gaseous metallicity even for the local galaxies with this method. We can only use the ratios of strong emission lines which are emitted from different ionization levels, to derive gaseous metallicities of high-z galaxies. There are several metallicity diagnostics that have been invented, namely \( R_{23} \) and N2 methods which can estimate gas-phase oxygen abundance, 12+log(O/H). However, different methods do not always give consistent oxygen abundances. Even if the same diagnostic is used, different calibrations lead to very different metallicities (Kewley & Dopita 2002; Kobulnicky & Kewley 2004). Therefore, one should make sure to use the same diagnostics and calibration in order to make any proper comparison with other results.

We derive gas phase metallicities of our [O II] emitters using the two diagnostics. One is based on Hα/[N II] flux ratios and its calibration by Pettini & Pagel (2004), and the other is based on Hβ/[O II] flux ratios and its calibration by Maiolino et al. (2008). Both diagnostics are not sensitive to dust extinction, because the wavelength difference of the pair lines is very small. If only either of the lines is detected, the upper/lower limit of metallicity is estimated. Fig. 17 shows thus derived metallicities of our [O II] emitters in the XCS2215 cluster plotted as a function of stellar mass. Fig. 17(a)
shows the metallicities from Hα/[N II] ratios, while Fig. 17(b) shows the metallicities from Hβ/[O III] ratios. Stellar masses are already derived in Section 5. In both the panels, we also show the mass–metallicity relations at different redshifts taken from the literature (Tremonti et al. 2004; Erb et al. 2006a; Maiolino et al. 2008) for comparison.

Although the error bars are large, Fig. 17 suggests that there is a weak mass–metallicity relation in the sense that more massive galaxies have higher metallicities. The metallicities of our [O III] emitters are comparable to those of the galaxies at z = 2–3 (Erb et al. 2006a; Maiolino et al. 2008). Our sample has the galaxies in a high-density galaxy cluster, while the samples of the above previous studies are the galaxies in the general field at z = 2–3. It seems that the star-forming galaxies in the cluster at z = 1.46 have a mass–metallicity relation similar to that of the field galaxies at z = 2–3. Although the redshift range is slightly different, this may suggest that the mass–metallicity relation is not very dependent on environment at z ≥ 1.5. Here, we must take into account the contribution of AGN to the line flux ratios. A larger contribution of AGN would make both [N II]/Hα and [O III]/Hβ larger, meaning that the derived metallicities are over-estimated with [N II]/Hα and underestimated with [O III]/Hβ, respectively. As discussed in the previous section, our [O III] emitters may have a moderate level of AGN contribution. In fact, the metallicities estimated by the two different line ratios are not in a good agreement. However, we can still trust the relative trend such as the existence of the mass–metallicity relation (but not its absolute values) as far as the same method is used uniformly. In order to quantify the evolution of the mass–metallicity relation at z ≥ 1.5, we need to evaluate the AGN contribution, but it is beyond the scope of this paper.

The fact that the mass–metallicity relation for the XCS2215 cluster is similar to that of the field at z ~ 2, may further support the lack of environmental dependence, due probably to the high star formation activity in the cluster cores at this high redshift comparable to that in the field.

8 SUMMARY

We conduct a wide-field survey of [O III] emission line galaxies in and around the XMMXCS J2215.9–1738 cluster at z = 1.46 with Subaru/Suprime-Cam. This survey is an extension of our previous study reported in Hayashi et al. (2010) which was limited to the central 6 × 6 arcmin² region of the cluster. By combining the UKIRT K imaging data, we have now extended the analyses to the entire 32 × 23 arcmin² region. We investigate colours and star formation activities of the [O III] emitters in various environments from the cluster core to the surrounding field at z = 1.46. Moreover, we conduct a follow-up near-infrared spectroscopy of 34 [O III] emitters in the cluster core identified in Hayashi et al. (2010) with Subaru/MOIRCS, and obtain JF spectra covering a wavelength range of 0.9–1.8 μm. These spectra enable us to confirm the existence of [O III] emission lines, and to investigate the detailed properties of the [O III] emitters on the basis of multiple nebular emission lines such as Hβ, [O III], Hα and [N II]. Our findings are summarized below.

(i) We select 380 [O III] emitters at z = 1.46 down to a line flux of 1.4 × 10⁻¹⁷ erg s⁻¹ cm⁻² in our entire survey area of 32 × 23 arcmin². The spatial distribution of the [O III] emitters shows a well-defined filamentary structure of star-forming galaxies to the east/south of the cluster as well as a concentration of such galaxies in the cluster core. The filament is one of the largest structures of star-forming galaxies at high redshifts (1.3 ≤ z ≤ 3). Based on the 2D structures, we define four different environments, namely, cluster core, outskirts, filament and the field, in order to investigate the environmental dependence of the properties of star-forming galaxies at z = 1.46.

(ii) We spectroscopically confirm that at least 16 [O III] emitters are certainly located at z = 1.46 out of 34 targeted [O III] emitter candidates in the cluster core. Only a single emission line is detected at ~9100 Å for three candidates. The other 15 candidates have no detected emission lines. However, the [O III] fluxes estimated by the narrow-band imaging suggest that it is likely that most of them have...
fluxes of emission lines smaller than the limiting flux. This thus assures that our photometric selection technique is valid to efficiently sample [O\textsc{ii}] emitters at $z = 1.46$. The redshift distribution of the confirmed emitters is consistent with that of the confirmed cluster members reported in Hilton et al. (2010), and is likely to have a double-peak feature.

(iii) The $z' - K$ versus $K$ colour–magnitude diagram shows a higher fraction of [O\textsc{ii}] emitters on the red sequence in the cluster region than that in the other environments. This suggests that some processes which work in the cluster core are responsible for the red colours of some [O\textsc{ii}] emitters. It is also noted that most of the red [O\textsc{ii}] emitters are massive galaxies. Their SEDs indicate that they are more likely passive galaxies with AGNs. We argue therefore that AGN feedback may be a good candidate for physical processes to quench star formation activities in massive galaxies in high-density regions.

(iv) The cluster (XMMXCS J2215.9–1738) has been conducting star formation at rates comparable to those in other environments. This supports our previous study (Hayashi et al. 2010) which found high star formation activities in the cluster central region. It is also found that the global specific star formation rate of galaxy cluster, which is calculated as the integrated SFRs divided by the integrated stellar masses of galaxies within a radius of $0.5 \times R_{200}$, increases with redshift up to $z = 1.46$.

(v) We investigate the flux ratios of emission lines, [O\textsc{iii}]/H$\beta$ and [N\textsc{ii}]/H$\alpha$, to distinguish between star-forming galaxies and AGNs. In a diagram showing both the line ratios, our [O\textsc{iii}] emitters are preferentially located in the intermediate, composite region where both star formation and AGN are likely to be contributing. It is therefore unlikely that many of the [O\textsc{ii}] emitters are heavily contaminated by strong AGNs, but at the same time it is likely that the AGN contribution is not negligible.

(vi) We estimate the strength of dust extinction from the Balmer decrement measurements ($H\beta$/$H\alpha$) for four of the [O\textsc{ii}] emitters where both the lines are detected. It is found that the extinction index $E(B - V)$ ranges from 0.40 to 0.91, suggesting that [O\textsc{ii}] emission line flux is considerably dependent on dust extinction.

(vii) We derive gas-phase metallicities for the [O\textsc{iii}] emitters from [N\textsc{ii}]/H$\alpha$ or [O\textsc{iii}]/H$\beta$ line ratios where available. It is found that our emitters in the cluster at $z = 1.46$ are located on a mass–metallicity relation, which is similar to that of the star-forming galaxies in the field at $z \sim 2$. This may also suggest that the star formation activity at $z \sim 1.5$ and beyond is not strongly dependent on environment.

In summary, we find that the star formation activity of galaxies at $z = 1.46$ is not yet strongly dependent on environment, and that even the cluster core is experiencing high star-forming activity comparable to those in other lower-density regions. Our results also suggest that a more detailed understanding of AGN activities along with star formation activities is crucial to revealing galaxy evolution in clusters, in particular the physical mechanisms of quenching in star formation. Larger, systematic near-infrared spectroscopic surveys such as those capable with Subaru/FMOS will enable us to understand the interrelationship between galaxy and AGN activities, and their co-evolution.

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