Identification of the progenitors of rich clusters and member galaxies in rapid formation at $z > 2$

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ABSTRACT

We present the results of near-infrared spectroscopy of H$_\alpha$ emitters (HAEs) associated with two protoclusters around radio galaxies (PKS 1138–262 at $z = 2.2$ and USS 1558–003 at $z = 2.5$) with the Multi-Object Infrared Camera and Spectrograph (MOIRCS) on the Subaru telescope. Among the HAE candidates constructed from our narrow-band imaging, we have confirmed membership of 27 and 36 HAEs for the respective protoclusters, with a success rate of 70 per cent of our observed targets. The large number of spectroscopically confirmed members per cluster has enabled us for the first time to reveal the detailed kinematical structures of the protoclusters at $z > 2$. The clusters show prominent substructures such as clumps, filaments and velocity gradients, suggesting that they are still in the midst of rapid construction to grow to rich clusters at later times. We also estimate the dynamical masses of the clusters and substructures, assuming their local virialization. The inferred masses ($\sim 10^{14} \, M_\odot$) of the protocluster cores are consistent with their being typical progenitors of the present-day most massive class of galaxy clusters ($\sim 10^{15} \, M_\odot$) if we take into account the typical mass growth history of clusters. We then calculate the integrated star formation rates of the protocluster cores normalized by the dynamical masses and compare these with lower redshift descendents. We see a marked increase of star-forming activities in the cluster cores, by almost three orders of magnitude, as we go back in time to 11 billion years ago; this scales as $(1 + z)^6$.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: formation.

1 INTRODUCTION

In protoclusters at $z > 2$, characteristic relations seen in low-$z$ clusters ($z < 1$), such as the colour–magnitude relation, break down as galaxies enter into their formation phase (Kodama et al. 2007). Since the galaxies in those protoclusters are destined to evolve into early-type galaxies in rich clusters today, the protoclusters provide us with unique laboratories in which to investigate directly the formation mechanisms of early-type galaxies and their environmental dependence, through comparison with field galaxies at similar redshifts. It is therefore essential to investigate the characteristics of protoclusters at $z > 2$ systematically, in order to know how star-forming (SF) activities in high-density regions at high $z$ are intrinsically biased and how they are affected externally by their surrounding environments to establish the strong environmental dependence seen in the present-day Universe.

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With this motivation, we have been conducting a systematic study of protoclusters at $z > 1.5$ with Subaru as the project ‘Mapping HAlpha and Lines of Oxygen with Subaru’ (Mahalo–Subaru: for more details see Kodama et al. 2013). We have conducted narrow-band (NB) imaging with many customized NB filters and have successfully identified H$_\alpha$ or [O III] emitter candidates that are physically associated with the protoclusters. The following two objects are among the richest systems ever identified: USS 1558–003 at $z = 2.53$ (Hayashi et al. 2012, hereafter H12) and PKS 1138–262 at $z = 2.16$ (Koyama et al. 2013, hereafter K13). Since they both show large excesses in number densities of SF galaxies, these protoclusters are probably still in the vigorous formation process. Our observations have revealed high SF activities towards the cores of protoclusters at $z > 2$. The peak of SF activity traced by the line emitters is shifted from dense cluster cores to lower density outskirts and filamentary outer structures with time from $z \sim 2.5$ to $z \sim 0.4$, indicating the inside-out growth of clusters.
These results are all intriguing, but we need to confirm them and
investigate the physical properties of protocluster galaxies in much
greater detail with spectroscopic follow-up observations. This Letter
reports the first results of our near-infrared (NIR) spectroscopy
of HAEs in the two richest protoclusters at $z > 2$. We first de-
scribe our targets and the method of spectroscopic observations
and then present the kinematical structures of spectroscopically
confirmed members. We also discuss SF activities in these two
systems through comparison with lower redshift counterparts. We
assume a $\Lambda$-dominated cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and
$H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2 Observation and Data Reduction

Our targets are selected on the basis of NB H$\alpha$ imaging together
with broad-band imaging of the two protoclusters around the
radio galaxies (RGs), namely PKS 1138–262 ($z = 2.16$) and
US$S$ 1558–003 ($z = 2.53$), hereafter PKS 1138 and USS 1558,
respectively. First we sample line emitters that show excess fluxes in
the near-band and then use a broad-band colour–colour diagram
($BzK$ or $rJK$) to separate H$\alpha$ emitters at the cluster redshift from
contaminant [O II]/[O III]/[O II]/Pa$\alpha$ emitters at other redshifts (see K13
and H12 for more details). We select the emitters with H$\alpha$ fluxes
larger than $2.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ as estimated from the NB
imaging (K13; H12), which corresponds to SFR $\sim 19$–25 M$_{\odot}$ yr$^{-1}$
for PKS 1138 and USS 1558, respectively, using the Kennicutt
(1998) conversion. We have identified 48 and 68 HAEs candi-
dates in the vicinity of PKS 1138 and USS 1558 respectively (K13;
H12). We used the Multi-Object Infrared Camera and Spectrograph
(MOIRCS), a NIR imager and spectrograph (Ichikawa et al. 2006;
Suzuki et al. 2008) mounted on the 8.2-m Subaru Telescope on
Mauna Kea. It provides a multi-object spectroscopic (MOS) capa-
bility at $\sim 0.9$–2.5 $\mu$m with a $4 \times 7$ arcmin$^2$ field of view covered
by two HAWAII-2 2048 $\times$ 2048 arrays with the spatial resolution
of 0.117 arcsec pixel$^{-1}$. We used a low-resolution grism (HK500:
$R \sim 500$ for 0.8 arcsec slit width) for 5 masks and a high-resolution
grism (VPH-K: $R \sim 1700$ for 0.8 arcsec slit width; see Ebizuka et al.
2011) for one of the 3 masks for PKS 1138. We made more than
15 slits per mask. In total, 98 objects were observed (some targets
were redundant).

We spent 5 nights (March–April in 2013) under 0.6–1 arcsec
seeing conditions for most of the time; however, one night was
completely lost due to bad weather. The net integration times were
longer than 2 h per mask. A summary of the observations is given
in Table 1.

### Table 1. Summary of the observations. Columns: (1) cluster name,
(2) grism name, (3) resolution with 0.8 arcsec slit width, (4) integra-
tion time and (5) the number of observed targets. HK500 and VPH-K
indicate low- and high-resolution grisms covering the ranges 1.3–2.5
and 1.9–2.3 $\mu$m, respectively.

| Cluster Name  | Grism   | R     | Integ. time | Targets |
|---------------|---------|-------|-------------|---------|
| PKS 1138–262  | HK500   | 513   | 120 min     | 23      |
| (11:40:48,−26:29:08) | HK500 | 513   | 161 min     | 19      |
| $z = 2.16$    | VPH-K   | 1675  | 225 min     | 18      |
| USS 1558–003  | HK500   | 513   | 180 min     | 25      |
| (16:01:17,+00:28:48) | HK500 | 513   | 276 min     | 19      |
| $z = 2.53$    | HK500   | 513   | 175 min     | 15      |

1 Available at http://www.naoj.org/Observing/DataReduction/
2 IRAF is distributed by National Optical Astronomy Observatory and avail-
able at http://iraf.noao.edu/
3 Available at http://www.stsci.edu/institute/software_hardware/stsdas/
This work revises that previous grouping to two clumps C1 and C2, with a small clump in between the two. The protocluster core. The radio galaxy PKS 1138 is right at the junction of the infalling filaments at the dynamical centre. The contamination level by foreground or background galaxies would then be $\sim 5$ per cent and thus has little impact on the current study.

4 DISCUSSION AND CONCLUSIONS

Kinematical structures of distant protoclusters provide essential information on the mass assembly history of galaxy clusters. Fig. 2 presents the spatial and redshift (or radialvelocity) distributions of the HAEs (and 15 confirmed LAEs in the case of PKS 1138). The blue and red symbols separate the members according to their redshifts or radial velocities: those approaching or receding, respectively, with respect to the radio galaxies.

From the velocity dispersion, we now estimate $R_{200}$ for each protocluster, which is the radius within which the averaged matter density is 200 times larger than the critical density. The dynamical mass of each system ($M_{\text{cl}}$) is also measured using the virial theorem (Finn et al. 2005), assuming local virialization.

4.1 PKS 1138–262 (z = 2.16)

PKS 1138 is among the most famous protoclusters at $z \sim 2$ and has been intensively studied by many researchers (e.g. Kurk et al. 2000).

We see some velocity structures across the protocluster (Fig. 2a) as well as the spatial structure. The galaxies near the RG within the dashed circle denoted as C1 seem to be relatively well mixed in velocity. However, the outer region is more structured. The most prominent structure is a linear filament extending towards the southeast direction from the RG. This almost perfectly aligned filament is dominated by approaching galaxies with respect to the RG, suggesting that those galaxies are falling on to the protocluster core along the filament and penetrating into the very centre. On the other hand, the north-west and east areas are preferentially occupied by receding populations. The south-west complex further away from the protocluster centre near the bottom right corner of the figure consists solely of approaching galaxies, suggesting the existence of a coherently moving group or filament.

All these spatial and kinematic structures seem to suggest that the inner part of the cluster centred on the RG ($<0.5$ Mpc) is already collapsed and nearly virialized, while the outer regions are still highly structured and are at the early phase of assembly towards the protocluster core. The radio galaxy PKS 1138 is right at the junction of the infalling filaments at the dynamical centre.

Upon the assumption of virialization in the core, the dynamical mass of the core is estimated at $1.71 \times 10^{14} M_{\odot}$ from the velocity dispersion of 683 km s$^{-1}$ within C1. X-ray observations of this system with the High Resolution Imager on ROSAT show that the emitted energy is $6.7 \pm 1.3 \times 10^{42}$ erg s$^{-1}$ in the 2–10 keV band, corresponding to the dynamical mass of $\sim 10^{14} M_{\odot}$. It is consistent with our result, although the X-ray emission is contaminated by active galactic nuclei (Carilli et al. 1998; Pentericci et al. 2002).

4.2 USS 1558–003 (z = 2.53)

USS 1558 is the densest protocluster ever known to date at $z > 2$ and was first discovered by Kajisawa (2006) and H12. H12 identified three groups of HAEs aligned along the north-east–south-west directions: a loose group around the RG, the richest clump at 3.5 arcmin away from the RG and a small clump in the between the two. This work revises that previous grouping to two clumps C1 and
The kinematical structures of HAEs in PKS 1138 (left) and USS 1558 clusters (right). Grey dots represent HAE candidates detected in our NB imaging (K13 and H12). Diamonds show the members newly confirmed in this study. Triangles are the confirmed Hα and [OII] emitters (LAE) in the previous works (Kurk et al. 2000, 2004; Croft et al. 2005; Doherty et al. 2010). Blue and red symbols are separated by blue- and redshifted galaxies, respectively, relative to the RGs (star mark). We identify three groups, namely PKS 1138-C1, USS 1558-C1 and USS 1558-C2, and they are shown by grey dashed circles. Solid and dotted black circles indicate $R_{200}$ and $0.5 \times R_{200}$, respectively.

C2 as shown in Fig. 2(b) because of the poor kinematical separation between the latter two clumps, identified only spatially in the previous study. We have now confirmed spectroscopically that the two groups are actually located at the redshift of the RG and are embedded in the large-scale structure. C2 is particularly rich, as it confines 19 spectroscopically confirmed HAEs and 12 more candidates (not confirmed yet) within a radius of 0.6 Mpc and is the densest system ever identified at high redshifts ($z > 2$). We note that the RG itself seems to be offset from this densest clump, unlike the PKS 1138 cluster.

Judging from the very high densities of the HAEs in compact areas, we could reasonably assume a local virialization in these regions and the corresponding dynamical masses and $R_{200}$ are estimated and listed in Table 2. The dynamical mass of C2 is estimated at $0.87 \times 10^{14} M_\odot$ from its velocity dispersion of 574 km s$^{-1}$.

We find that there is a large-scale velocity gradient across the cluster in the direction of the group alignment (north-east–south-west). The velocity distribution and central value of the south-west group (C2) are blueshifted from those of the north-east group (C1) that hosts the RG (Fig. 2; see also Table 2). Therefore those groups are probably physically aligned and gravitationally pulling each other closer. They would eventually merge together and become a single rich cluster in the near future.

4.3 Cosmic evolution of $\Sigma SFR/M_{cl}$

Finally, we investigate the cosmic SF history in galaxy clusters represented by the integrated SFR ($\Sigma SFR$) normalized by cluster dynamical mass (Fig. 3a). In order to compare our results directly with the previous works compiled by Finn et al. (2005), we sum up individual SFRs of the Hα (or [OII]) emitters within $0.5 R_{200}$, including the candidates whose membership has not been confirmed yet. In this work, we calculate $\Sigma SFR$ and $M_{cl}$ for the main body of the PKS 1138 cluster (C1) and the richest clump of the USS 1558 cluster (C2), respectively. We assume a uniform dust extinction of $A_{H\alpha} = 1$ and $A_{[OIII]} = 1.76A_{H\alpha}$. To evaluate the uncertainties from this assumption, we also estimate $\Sigma SFR$ within $R_{200}$, employing the mass-dependent correction for dust extinction (Garn & Best 2010). Although the absolute values of $\Sigma SFR$ may have large systematic errors, due to various factors such as sampling bias, active galactic nucleus contribution and so on, the relative differences among different clusters that we see here are more reliable. Koyama et al. (2010, 2011) found that $\Sigma SFR/M_{cl}$ in cluster cores increases dramatically to $z \sim 1.5$ and scales as $(1+z)^6$ (see also Smail et al. 2014). We find that this trend extends to even higher redshifts to $z \sim 2.5$, as our values of $\Sigma SFR/M_{cl}$ within $R_{200}$ estimated in this work seem to more or less follow the extrapolated curve of the redshift evolution.

In such comparisons of clusters at different redshifts, we must be sure that we are comparing the right ancestors with the right descendants. In fact, clusters grow in mass with cosmic time by a large factor and therefore we should compare galaxy clusters taking into account such mass growth. Fig. 3(b) shows cluster masses as a function of redshift. The red line and the pink zone show the mass growth history of massive cluster haloes predicted by cosmological simulations (Shimizu et al. 2012; Chiang et al. 2013). The data points show the measurements of the dynamical masses of real clusters used for comparison. It turns out that our protoclusters at $z > 2$ have large enough masses to be consistent with the progenitors of the most massive class of clusters, like Coma. The lower-$z$ clusters, shown with filled squares, also follow the same mass growth curve. Therefore we argue that we are comparing the right ancestors with the right descendants and the redshift variation of the mass-normalized SFRs seen in the upper panel can be seen as the intrinsic cosmic SF history of the most massive class of clusters.

In this Letter, we have presented the kinematical structures of the two richest protoclusters at $z > 2$ and extended the cosmic evolution...
of $\Sigma\text{SFR}/M_\odot$ back to $z > 2$ or 11 Gyr ago, based on intensive multi-object NIR spectroscopy of the NB-selected star-forming galaxies. In our forthcoming Paper II (in preparation), we will discuss the physical properties of these galaxies (such as gaseous metallicities, ionizing states and dust extinction) using multi-emission-line diagnostics and compare them with those in the general field at similar redshifts.

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