An H\(\alpha\) search for over-dense regions at z = 2.23*

Y. Matsuda,1† Ian Smail,2 J. E. Geach,3 P. N. Best,4 D. Sobral,4 I. Tanaka,5 F. Nakata,5 K. Ohta,6 J. Kurk,7 I. Iwata,5 Rich Bielby,1 J. L. Wardlow,8 R. G. Bower,2 N. Fanidakis,2 R. J. Ivison,4,9 T. Kodama,5 T. Yamada,10 K. Mawatari10 and M. Casali11

1 Department of Physics, Durham University, South Road, Durham, DH1 3LE
2 Institute for Computational Cosmology, Durham University, South Road, Durham, DH1 3LE
3 Department of Physics, McGill University, 3600 Rue University, Montreal, QC H3A 2T8, Canada
4 SUPA, Institute for Astronomy, Royal Observatory of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ
5 Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place Hilo, HI 96720, USA
6 Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan
7 Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, 85741 Garching, Germany
8 Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
9 UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ
10 Astronomical Institute, Graduate School of Science, Tohoku University, Aramaki, Aoba-ku, Sendai 980-8578, Japan
11 European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85738 Garching, Germany

Accepted ... ; Received ... ; in original form ...

ABSTRACT

We present the results of a narrow-band (H\(\alpha\)S1, \(\lambda_c = 2.121\mu m\), \(\delta \lambda = 0.021\mu m\)) imaging search with WFCAM/UKIRT for H\(\alpha\) emitters around several potential signposts of rare (\(\sim 10^{-7} - 10^{-8}\) Mpc\(^{-3}\)) over-dense regions at z = 2.23: an over-density of QSOs (2QZ cluster), a powerful, high-redshift radio galaxy (HzRG), and a concentration of submillimetre galaxies (SMGs) and optically faint radio galaxies (OFRGs). In total, we detect 137 narrow-band emitter candidates down to emission-line fluxes of \(0.5 - 1 \times 10^{-16}\) erg s\(^{-1}\) cm\(^{-2}\), across a total area of 0.56 sq. degrees (2.1 \(\times 10^5\) comoving Mpc at z = 2.23) in these fields. The \(BzK\) colours of the emitters suggest that at least 80% of our sample are likely to be H\(\alpha\) emitters (HAEs) at z = 2.23. This is one of the largest HAE samples known at z \(\gtrsim 2\). We find modest (\(\sim 3\sigma\)) local over-densities of emitters associated with all the three targets. In the 2QZ cluster field, the emitters show a striking filamentary structure connecting four of the z = 2.23 QSOs extending over 30 Mpc (comoving). In the HzRG and SMG/OFRG fields, the structures appear to be smaller and seen only in the vicinities of the targets. The K-band magnitudes and the H\(\alpha\) equivalent widths of the emitters are weakly correlated with the over-density of the emitters: emitters in over-dense region are more evolved systems compared to those in under-dense regions at z = 2.23. We find several examples of extended HAEs in our target fields, including a striking example with a spatial extent of 7.5 arcsec (60 kpc at z = 2.23) in the 2QZ field, suggesting that these are relatively common in high-density regions. We conclude that narrow-band H\(\alpha\) surveys are efficient routes to map over-dense regions at high-z and thus to understand the relation between the growth of galaxies and their surrounding large-scale structures.

Key words: galaxies: formation – galaxies: evolution – galaxies: high-redshift – cosmology: observations – early Universe

* Based on observations obtained with the Wide Field CAMera (WFCAM) on the United Kingdom Infrared Telescope (UKIRT), and in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan, and collected at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration.
† E-mail: yuichi.matsuda@durham.ac.uk
1 INTRODUCTION

Local galaxy clusters are characterised by populations of passive, early-type galaxies, whose properties contrast markedly with the star-forming, late-type galaxies found in the surrounding low-density field (e.g. Dressler 1980). The main formation phase of the stars in elliptical galaxies in clusters appears to have occurred at high redshift (probably $z \geq 2$, e.g. Ellis et al. 1997; Blakeslee et al. 2003; Mei et al. 2009), in contrast to the field where most of the star-formation activity occurs at $z \lesssim 2$ (e.g. Lilly et al. 1993; Thomas et al. 2005). Hence the evolution of galaxies in clusters appears to be accelerated relative to that in low-density regions (e.g. Steidel et al. 2002; Tanaka et al. 2010; Tadaki et al. 2010; Hatch et al. 2011). As a result, while the average star-formation rate (SFR) of a galaxy decreases with increasing local galaxy density in the low-redshift Universe (e.g. Lewis et al. 2002; Gómez et al. 2004), this trend should reverse at earlier times: with the SFR increasing with increasing galaxy density (Elbaz et al. 2007; Hayashi et al. 2010; Tran et al. 2010; Grützbauch et al. 2011). Hence the progenitors of massive clusters at high-redshifts (proto-clusters) should be identifiable as over-densities of star-forming galaxies (Steidel et al. 1998, 2003; Venemans et al. 2007; Matsuda et al. 2009, 2010). If the growth of the galaxies is synchronised with that of their super-massive black holes, then populations of active galactic nuclei should also be located in these proto-clusters (Smail et al. 2003; Lehmer et al. 2004; Digby-North et al. 2010).

To identify proto-clusters, the most representative, but time-consuming, technique is to find significant redshift over-densities in large spectroscopic redshift surveys of star-forming galaxies (Steidel et al. 1998, 2003; Chapman et al. 2004; Kurk et al. 2009). A quicker route is to perform such searches around luminous high-redshift sources, such as quasi-stellar objects (QSOs) or powerful high-redshift radio galaxies (HzRGs), where the expectation is that the massive black holes in these galaxies will be hosted by correspondingly massive galaxies which will signpost over-dense regions at high redshifts. An even more efficient technique is to forego spectroscopy and instead search for concentrations of emission-line galaxies in narrow-band imaging surveys of these regions (e.g. Hu & McMahon 1996; Pascarelle et al. 1996; Keel et al. 1999; Kurk et al. 2004, 2004a, b; Venemans et al. 2007; Kashikawa et al. 2005; Tanaka et al. 2010; Hatch et al. 2011).

For target QSOs or HzRGs at $z > 2$, Ly$\alpha$ is redshifted into the optical and hence most of the narrow-band imaging surveys have targeted Ly$\alpha$ emission. However, Ly$\alpha$ is far from ideal as it is a resonance line and even a small amount of dust is enough to destroy the line, thus biasing searches against the dusty and perhaps most active galaxies in any structure. A better choice is to use H$\alpha$, which is less sensitive to dust and also a more accurate tracer of star formation (Kennicutt 1998; Garn et al. 2010). However, for galaxies at $z > 0.4$, H$\alpha$ is redshifted into the near-infrared, and it is only through the recent development of panoramic, near-infrared imagers that narrow-band searches based on H$\alpha$ have become possible (Sobral et al. 2009a, b, 2010b, 2011; Geach et al. 2008, hereafter G08).

We have exploited the wide-field, near-infrared imaging capabilities of WFCAM on UKIRT (Casali et al. 2007)

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{The transmission curves of the H$\alpha$ filter on UKIRT/WFCAM. We identify the wavelengths for H$\alpha$ emitters expected for the redshifts of our various targets: the QSOs in the 2QZ structure, the HzRG MRC0200+015 and the SMG/OFRGs in SAA 13. The mean redshifts of the three sets of targets are clearly well-matched to the transmission of the filter, allowing us to efficiently survey for H$\alpha$ emitters in any associated structures.}
\end{figure}

to carry out an H$\alpha$ imaging survey around several potential signposts of over-dense regions at $z = 2.23$. The paper is structured as follows: §2 describes our target selection, while §3 details our observations and data reduction and §4 describes the results derived from these data. Finally, §5 discusses our results and summarises our main conclusions. We use Vega magnitudes unless otherwise stated and adopt cosmological parameters, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 73\, \text{km s}^{-1}\, \text{Mpc}^{-1}$. In this cosmology, the Universe at $z = 2.23$ is 2.9 Gyr old and 1.0 arcsec corresponds to a physical length of 8.1 kpc.

2 TARGET FIELD SELECTION

Our survey uses the H$\alpha$1 narrow-band filter on WFCAM to isolate H$\alpha$ emitters at $z = 2.23$. We plot the transmission curve of the narrow-band filter (H$\alpha$1, $\lambda_c = 2.121\mu\text{m}$, $\delta\lambda = 0.021\mu\text{m}$) in Figure 1. The redshift range of the H$\alpha$ line corresponding to the 50% transmission wavelengths of the filter is $z = 2.216$–2.248 (equivalent to a comoving length of 43.1 Mpc along the line of sight). We therefore searched for targets which could be potential signposts of over-dense regions at $z \sim 2.23$ using the NASA/IPAC Extragalactic Database (NED).\footnote{The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.} We selected three targets: an over-density of QSOs, a HzRG, and a concentration of submillimetre galaxies (SMGs) and optically faint radio galaxies (OFRGs). We summarise the targets in Table 1.

2.1 2QZ cluster

Our first target is a concentration of QSOs selected from the 2dF QSO redshift survey (2QZ, Croton et al. 2001). There now appears to be some consensus that on average, over-densities of galaxies are present around typical QSOs (both radio-loud and quiet) at $z < 2$ (e.g. Ellingson, Yee, & Green
Table 1. Summary of targets

| Field       | Target                          | Redshift | Magnitude | Ref. a |
|-------------|---------------------------------|----------|-----------|--------|
| 2QZ cluster | 2QZ J100351.5+001501             | 2.217    | B = 20.43 | 1      |
|             | 2QZ J100412.8+001257             | 2.240    | B = 18.57 | 1, 2   |
|             | 2QZ J100339.7+002109             | 2.241    | B = 19.58 | 1, 2   |
|             | 2QZ J100323.0+000725             | 2.235    | B = 20.57 | 1, 2   |
|             | 2QZ J100204.0+001643             | 2.245    | B = 20.42 | 1, 2   |
| 0200+015    | NVSS J020242+014910              | 2.229    | H = 19.26 | 3, 4, 5, 6 |
| SSA 13      | SMM J131230.92+424051.0          | 2.247    | K = 19.29 | 7      |
|             | SMM J131239.14+421555.7          | 2.242    | K = 19.49 | 7      |
|             | RG J131207.74+423945.0           | 2.228    | K = 19.36 | 8      |
|             | RG J131208.34+424144.4           | 2.234    | K = 19.10 | 8      |
|             | RG J131236.05+424044.1           | 2.224    | K = 20.50 | 8      |

a (1) Croom et al. (2004), (2) Shen et al. (2007), (3) Large et al. (1981), (4) Röttgering et al. (1997), (5) Condon et al. (1998), (6) Iwamuro et al. (2003), (7) Chapman et al. (2005), (8) Smail et al. (2004).

b This source is just outside of the WFCAM field of view.

c This source is outside of the WFCAM field of view.

1991; Hall & Green 1998). However, using over-densities of QSOs should be a much clearer marker of structures at high redshift (Clowes & Campusano 1991). We searched the whole equatorial region from the 2QZ survey for regions with more than four QSOs at \( z = 2.16 - 2.248 \) in a 1-degree diameter field. There are 285 QSOs at \( z = 2.216 - 2.248 \) in the 2QZ survey area of \( 28.6 \text{ deg}^2 \) (or \( 1.1 \times 10^8 \text{ comoving Mpc} \)). We found only one structure satisfying the criteria in this volume indicating a volume density of any associated structure of \( \sim 10^{-8} \text{ comoving Mpc}^{-3} \). We refer to this target as the 2QZ cluster, it contains five QSOs at \( z = 2.217, 2.235, 2.240, 2.241 \), and 2.245 (see Figure 1 and Table 1). Four out of the five QSOs are even more strongly clustered in a \( 15 \times 15 \text{ arcmin}^2 \) region, with three of these QSOs falling within the field of view of a single WFCAM chip, with the fourth located just outside the field of view.

### 2.2 0200+015

Our second target is a HzRG: MRC 0200+015. The number density of HzRGs at \( z = 2 - 5 \) is a few times \( 10^{-8} \text{ Mpc}^{-3} \) (Miley & Breuck 2007), and thus HzRGs are quite rare. There is growing evidence that a significant fraction of HzRGs reside in over-dense environments (Kurk et al. 2004; Pentericci et al. 2000; Stevens et al. 2003; Smail et al. 2003; Miley et al. 2004; Kajisawa et al. 2006; Kodama et al. 2007; Venemans et al. 2007; Tanaka et al. 2010; Hatch et al. 2011). However, Best et al. (2003) show that HzRG at \( z \sim 1.5 - 2 \) are found in a very wide range of environments, from essentially no-over-density, through a small-scale central over-density to larger scale over-densities. Using NED, we identified a HzRG, MRC 0200+015 (or NVSS J020242+014910) at \( z = 2.229 \) (hereafter 0200+015, Large et al. 1981; Röttgering et al. 1997; Condon et al. 1998). This HzRG field was observed using Hα imaging by van der Werf, Moorwood, & Bremer (2000). They imaged an area of just \( 6.37 \text{ arcmin}^2 \) down to a \( 3 \sigma \) flux limit of \( 1.0 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \) for Hα emitters in redshift range of \( z = 2.19 - 2.26 \). Although they detected the HzRG as an Hα emitter, they did not identify any additional Hα emitter candidates around the HzRG. A single WFCAM chip has a field of view \( \sim 30 \text{ times larger} \) than the area surveyed by van der Werf, Moorwood, & Bremer (2000), giving us the first opportunity to conclusively search for a structure around this HzRG.

### 2.3 SSA 13

Our final target is a potential concentration of massive starburst galaxies. From redshift surveys of SMGs and OFRGs, a significant redshift spike was discovered at \( z = 2.242 - 2.247 \) (\( \Delta z = 0.023 \)) in the Small Selected Area 13 (SSA 13) field (Smail et al. 2004; Chapman et al. 2005). This spike contains two SMGs at \( z = 2.242, 2.247 \), and three OFRGs at \( z = 2.224, 2.228, \) and 2.234 (see Figure 1 and Table 1). This spike is one of the most prominent structures in their survey volume of a few times \( 10^6 \text{ Mpc}^{-3} \) comoving Mpc, suggesting a structure with a number density of a few times \( 10^{-7} \text{ Mpc}^{-3} \) (c.f. Chapman et al. 2004).

### 3 OBSERVATIONS AND DATA REDUCTION

#### 3.1 WFCAM Observations

The three target fields were observed between 2006 May and 2010 April with WFCAM on UKIRT, using the \( K \)-band and \( H \)S1 filters. We summarise the observations in Table 2. WFCAM has four \( 13 \times 13 \text{ arcmin}^2 \) chips offset by 20 arcmin (a comoving separation of \( 32 \text{ Mpc} \) at \( z = 2.23 \)). For our observations we place the target on one of the chips (Chip 1 for the 2QZ cluster and SSA 13, Chip 3 for 0200+015), with the other three chips providing control fields to derive the mean density of emitters \( \sim 40 - 60 \text{ Mpc} \) (comoving) away from the other emitters.
Table 2. Summary of observations and data

| Field       | Coordinate (J2000) (h:m:s) (d:m:s) | Date (mm/yyyy) | Filter | Chip | Exp time (ks) | Deptha (mag) | FWHM (arcsec) | Area (arcmin²) | Number densityb (arcmin⁻²) |
|-------------|------------------------------------|----------------|--------|------|--------------|--------------|---------------|----------------|--------------------------|
| 2QZ cluster | 10:03:51.0 +00:15:09 02/2010 H₂S₁ 1 | 34.44 | 19.9 | 0.9 | 196 | 8.1 (H₂S₁<19.9) |
|             | 10:05:37.2 +00:15:03              | 34.44 | 20.0 | 0.9 | 171 | 9.6 (H₂S₁<19.9) |
|             | 10:05:37.8 +00:41:22              | 34.44 | 19.9 | 0.9 | 172 | 10.1 (H₂S₁<19.9) |
|             | 10:03:51.5 +00:41:33              | 34.44 | 20.1 | 0.9 | 171 | 8.6 (H₂S₁<19.9) |
|             | 10:03:51.0 +00:15:09 02-03/2010 K 1 | 4.48 | 20.4 | 0.7 | 169 | 8.2 (K<19.9) |
|             | 10:05:37.2 +00:15:03              | 4.48 | 20.3 | 0.8 | 171 | 10.0 (K<19.9) |
|             | 10:05:37.8 +00:41:22              | 4.48 | 20.4 | 0.8 | 172 | 10.3 (K<19.9) |
|             | 10:03:51.5 +00:41:33              | 4.48 | 20.3 | 0.8 | 171 | 8.8 (K<19.9) |
| 0200+015    | 02:02:42.6 +01:50:54 10/2007 H₂S₁ 3 | 13.44 | 19.6 | 0.9 | 148 | 8.3 (H₂S₁<19.5) |
|             | 02:00:56.0 +01:24:38              | 13.44 | 19.6 | 1.0 | 172 | 8.1 (H₂S₁<19.5) |
|             | 02:02:42.2 +01:24:35              | 13.44 | 19.7 | 1.1 | 169 | 7.2 (H₂S₁<19.5) |
|             | 02:00:56.1 +01:51:02              | 13.44 | 19.5 | 1.0 | 174 | 6.5 (H₂S₁<19.5) |
|             | 02:02:42.6 +01:50:54 10/2007 K 3   | 1.335 | 20.1 | 1.0 | 148 | 8.0 (K<19.5) |
|             | 02:00:56.0 +01:24:38              | 1.23  | 20.1 | 1.1 | 172 | 8.0 (K<19.5) |
|             | 02:02:42.2 +01:24:35              | 1.25  | 20.1 | 1.0 | 169 | 7.4 (K<19.5) |
|             | 02:00:56.1 +01:51:02              | 1.365 | 20.0 | 1.2 | 174 | 6.5 (K<19.5) |
| SSA 13      | 13:12:34.1 +42:40:43 05/2006 H₂S₁ 1 | 14.76 | 19.0 | 0.9 | 146 | 4.2 (H₂S₁<19.0) |
|             | 13:14:58.5 +42:40:49              | 14.32 | 19.1 | 0.9 | 174 | 5.1 (H₂S₁<19.0) |
|             | 13:14:58.2 +43:07:03              | 14.56 | 19.1 | 0.9 | 174 | 4.9 (H₂S₁<19.0) |
|             | 13:12:33.2 +43:07:08              | 14.96 | 19.1 | 0.9 | 171 | 4.6 (H₂S₁<19.0) |
|             | 13:12:34.1 +42:40:43 05/2006 K 1   | 0.625 | 19.7 | 1.0 | 147 | 4.3 (K<19.0) |
|             | 13:14:58.5 +42:40:49              | 0.615 | 19.7 | 0.9 | 174 | 5.0 (K<19.0) |
|             | 13:14:58.2 +43:07:03              | 0.63  | 19.8 | 0.9 | 174 | 4.8 (K<19.0) |
|             | 13:12:33.2 +43:07:08              | 0.62  | 19.5 | 0.9 | 171 | 4.7 (K<19.0) |

The number density of H₂S₁ detected sources.

The data reduction was carried out in the same manner as for the HIZELS survey (G08, Sobral et al. 2009, 2011, 2013). We flatfield a given image using a normalised median combination of the 13 remaining frames from the same sequence, taking care to mask-out bright sources in each frame. A world coordinate system is then automatically fit to each frame by querying the USNO A2.0 catalogue, on average returning ~100 sources to derive the astrometric fit. Frames are aligned and co-added with SWARP (Bertin et al. 2002). Both K-band and H₂S₁ magnitudes were calibrated by matching K ~10–15 stars from the 2MASS All-Sky Catalogue of Point Sources (Cutri et al. 2003) which are unsaturated in our frames. The magnitudes were not corrected for Galactic extinction, because the extinction is negligible in these bands (≪ 0.01 mag. Schlegel, Finkbeiner, & Davis 1998).

The combined images were aligned and smoothed with Gaussian kernels to ensure that the final images in each field have the same seeing (FWHM = 0.9–1.2 arcsec). The size of each chip analyzed here is 13.2 × 13.2 arcmin² after removal of low S/N regions near the edge. We also masked out halos and cross-talk residuals of the bright stars (K < 15). The resultant total effective area of each chip is ~150–170 arcmin² (corresponding to a comoving volume of ~1.6–1.8 × 10⁶ Mpc³ for Hα emitters at z = 2.23 in the H₂S₁ filter).

Source detection and photometry were performed using SExtractor version 2.5.0 (Bertin & Arnouts 1996). The detected sources were made on the H₂S₁ image. We detected sources with five connected pixels above 1.0–1.5σ of the sky noise. Each WFCAM chip has four amplifiers, we microstepped in a 2 × 2 grid with 1.2 arcsec offsets at each position, following a 14-point jitter sequence. The seeing in our observations varied between 0.7–1.2 arcsec FWHM.
3.2 Supporting Observations

3.2.1 SCAM Observations

To check contamination in our emitter sample from foreground and background line emitters, we obtained B and z′-band images of the target fields with Subaru/Suprime-Cam [Miyazaki et al. 2002]. We observed the 2QZ cluster field in 2009 November and the 0200+015 field in 2010 November. For the SSA 13 field, we used archival data. All the images were a single pointing of Suprime-Cam, covering only one chip of the WFCAM observations. The exposure times were 0.9–3.0 ks for the B-band and 0.9–1.8 ks for the z′-band, respectively. The data were reduced using sofred [Yagi et al. 2002, Ouchi et al. 2004]. For photometric calibration, we used the photometric standard stars in SA 101 field [Landolt 1992, Smith et al. 2002] and SDSS z′-band images for the 2QZ cluster and SSA 13 fields. We corrected the magnitudes using the Galactic extinction map of Schlegel, Finkbeiner, & Davis [1998]. The seeing of the stacked images are 0.9–1.2 arcsec for B-band and 0.6–0.8 arcsec for z′-band, respectively. The 1σ limiting AB magnitudes derived with 3 arcsec diameter aperture photometry are 27.0–27.6 ABmag for B-band and 25.6–26.0 ABmag for z′-band, respectively.

3.2.2 MOIRCS Observations

The 0200+015 field was also observed with the Ks-band and H2S1 filters using Subaru/MOIRCS [Suzuki et al. 2008] in 2007 August as part of engineering tests (performed by IT). The H2S1 filter on MOIRCS has λc = 2.116μm and δλ = 0.021μm. The Hα redshift range covered with the H2S1 filter is z = 2.208–2.240, which is only Δz = 0.008 smaller than that covered with the H2S1 filter on WFCAM. As one of the two chips had problems, we used only one chip. The exposure times were 1.17 ks for Ks-band and 1.44 ks for H2S1, respectively. We reduced the data using the MOIRCS imaging data reduction pipeline.
In addition, we carried out a long-slit spectroscopic observation of a bright emitter candidate in the 0200+015 field with Keck/LRIS (Oke et al. 1995) in 2010 September. We obtained 1.2 ks of exposure using a 0.9 arcsec diameter aperture of 22.3 mag for $K_s$-band and 21.0 mag for H$_2$S1. The deeper, higher resolution images can be used as a test of the completeness of our WFCAM observations and to examine the continuum morphology in the central 4 × 3.5 arcmin$^2$ part of the 0200+015 field. These data will be discussed further in I. Tanaka et al. (in preparation).

### 3.2.3 LRIS Observations

In addition, we carried out a long-slit spectroscopic observation of a bright emitter candidate in the 0200+015 field with Keck/LRIS (Oke et al. 1995) in 2010 September. As the red-side CCD had problems, we used only the blue arm. We used the 400/3400 grism and a 1.0 arcsec slit, yielding spectral coverage across $\sim$3500–5700 Å, at a spectral resolution of FWHM $\sim$7 Å or $\sim$600 km s$^{-1}$. The exposure time was 0.9 ks and we reduced the data with standard IRAF tasks. For wavelength calibration, we used arc lamp spectra with Hg, Cd, and Zn lines, giving a wavelength calibration with an rms $\sim$0.6 Å. We also confirmed that there is no overall shift ($\lesssim 0.2$ Å) for the wavelength calibration using the strong [O(i)] sky emission at 5577.3 Å.

### 4 ANALYSIS AND RESULTS

We show in Figure 2 the colour–magnitude plots for the H$_2$S1-detected sample. From the H$_2$S1-detected sources with H$_2$S1 $\geq 5\sigma$ in each field, we select emitter candidates with the following criteria:

1. $K - H_2$S1 $\geq 0.215$ (EW$_{obs} \geq 50$ Å).
2. $\Sigma \geq 2.5$,

where $\Sigma$ is the ratio between the H$_2$S1 excess and the uncertainty in the $K - H_2$S1 colour based on photometric errors of both $K$ and H$_2$S1 for sources with a constant $J_F$ spectra. These criteria are the same as used in G08. One slight difference from G08 is that we don’t correct the $K$-band magnitudes using the $z' - K$ colour for the emitter selection, because we don’t have $z'$-band images in our control fields. As we show below, this does not appear to adversely affect the purity of our narrow-band excess sample. We note that in each field, the limiting magnitudes between the chips are slightly different and so we use the shallowest 5σ limits and significance curves for the colour cut for both the targets and the surrounding control fields to ensure a fair comparison of the number density in each field. The colour cuts correspond to flux limits of $\sim 0.5, \sim 0.7$ and $\sim 1.0 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ for the 2QZ cluster, 0200+015 and SSA 13 fields respectively.

In total we detect 137 emitter candidates over a combined area of 0.56 sq. degrees ($2.1 \times 10^5$ comoving Mpc$^3$ at $z = 2.23$) in the three fields. A flux limit of $0.5 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ corresponds to a star-formation rate (attenuation-uncorrected) of SFR $\sim 14$ M$_\odot$ yr$^{-1}$ using the calibration of Kennicutt (1998) or SFR $\sim 70$ M$_\odot$ yr$^{-1}$ (attenuation-corrected) using the reddening estimates from Garn et al. (2010). We listed the resulting catalogue of emitter candidates in the tables in Appendix A.

We have used the Suprime-Cam optical imaging to investigate the contamination from potential foreground and background line emitters (e.g., Paa emitters at $z = 0.13$, Pa[$\beta$] emitters at $z = 0.65$ and [O(i)]5007 emitters at $z = 3.24$). We show in Figure 3 the $B - z'$ and $z' - K$ colour-colour plot for emitter candidates in the target fields. This $BzK$ colour–colour plane allows us to isolate $z \sim 1.4$–2.5 galaxies (Daddi et al. 2004), which are likely to be Ho emitters (HAEs), from any foreground or background contamination (see G08). Although the $BzK$ criteria, $BzK \equiv (z-K)_{AB} - (B-z)_{AB} \geq -0.2$ or $(z-K)_{AB} > 2.5$, were determined using a $BzK$ filter set from different instruments, it has been confirmed that the same criteria can also be used for Suprime-Cam $B$ and $z'$, and WFCAM $K$-bands to select $z \sim 1.4$–2.5 galaxies (e.g., Havashi et al. 2009). We find that $\geq 80\%$ of the emitter candidates satisfy the $BzK$ criteria, indicating that these are likely to be $z \sim 2.23$ HAEs. Note that the three QSOs in the 2QZ cluster field are slightly outside the $BzK$ colour–colour region ($BzK \sim 0.0$–0.2 mag), even though they are spectroscopically confirmed at $z \sim 2.23$. As the $BzK$ analysis was designed for galaxies, and not for AGNs, this is perhaps not that surprising.

The apparent contamination rate in our candidate emitter sample, $\sim 20\%$ is similar to the $\sim 10$–$20\%$ rates in other Ho emitter surveys for protoclusters (Tanaka et al. 2010, Hatch et al. 2011). Although our contamination rate seems to be lower than the $\sim 50$–$70\%$ rates in other Ho emitter surveys in blank fields (G08; Hayes, Schaerer, Ostlin 2010, Hatch et al. 2011), we have used the $\sim 30\%$ rate for the sub-sample of [Havashi, Schaerer, Ostlin (2010)]’s emitters with the similar flux range to our sample. As we show below, the resulting Ho luminosity functions of our emitters (in both target and control fields) and G08’s HAEs are consistent, supporting the low contamination in our HAE sample.
Figure 3. BzK diagram for emitter candidates in the target fields. At least 80% of the emitter candidates satisfy the BzK criteria, $BzK \equiv (z - K)_{AB} - (B - z)_{AB} \geq -0.2$ or $(z - K)_{AB} > 2.5$ (Daddi et al. 2004), indicating that these are likely to be Hα emitters at $z = 2.23$. This plot suggests that the contamination rate from potential foreground and background line emitters in our emitter sample is $\lesssim 20\%$. The squares indicate the target QSOs, HzRG. The HAE17 with an extended emission-line nebula in the 2QZ cluster field and spectroscopically confirmed narrow-line AGN (NLAGN) at $z = 2.235$ in the 0200+015 field are also marked.

Figure 4. The Hα luminosity function (LF) in the target and control fields. The LFs in the target (filled symbol) and control fields (open symbol) appear to be consistent with that of the blank field. We exclude the QSOs and HzRG from the emitter sample used to derive the LF. As the contamination rate is $\lesssim 20\%$ in our emitter sample in the target fields, we assume all the emitter candidates are Hα emitters in this plot. The dashed line shows the blank field Hα luminosity function at $z = 2.23$ from Geach et al. (2008). The dotted lines represent the detection limits of our emitter sample. The data points in the control fields are slightly shifted ($\sim 0.1$ dex) for display purposes.

Note that for the following comparison of the number density between the target and control fields, we have to use the full sample of emitter candidates (i.e., before applying the BzK criteria) because we lack optical images in our control fields. However, due to our low contamination rate this only slightly affect the significance of the over-densities we find in these fields.

In Table 3, we summarise the number, number density, and over-density of the emitter candidates in each field. We derive the mean emitter densities using the surrounding control fields for each target field. Our analysis of the number densities suggests that there is no significant excess of emitters in any of the three target fields on the scale of the WFCAM chips (22 comoving Mpc at $z = 2.23$). Note that in the 2QZ cluster field, the number of emitter candidates on chip 4 appears to be lower than on the other chips. However, we have confirmed that across all fields the total number of all H2S1-detected sources (not just those showing excess emission in the H2S1 filter) on chip 4 is not different with those in the other chips, as shown in Table 2. Thus, the lower numbers of the emitter candidates on chip 4 in the 2QZ cluster field are likely to be real (i.e., a void of emitters).

We compare the Hα luminosity functions (LF) of the emitter candidates in the target and control fields in Figure 4. All the LFs appear to be consistent with the blank field LF of $z = 2.23$ HAEs from G08. We could not find...
any clear difference between the shapes of LFs in the target and control fields. In this comparison, we have excluded the three QSOs and HzRG from our emitter sample.

To search for over-densities on scales smaller than the chip field-of-view, we show in Figure 5 the sky distribution and smoothed density map of emitter candidates in the target fields. The surface density maps are generated with a gaussian smoothing kernel with a size chosen to match the median distance between the nearest-neighbour emitters in the control fields, $\sigma = 1.4$ arcmin for the 2QZ cluster and 0200+015, and $\sigma = 2.3$ arcmin for SSA 13. In these maps, we can see modest over-densities ($\sim 3\sigma$ deviations from
the average densities) of emitters within all three target fields. In the 2QZ cluster field, the emitters appear to have a filamentary structure connecting the four QSOs, while in the HzRG and SMG/OFRG fields, the structures appear to be smaller and only seen in the vicinities of the targets. We discuss these structures below, but we first note that the estimated significance of these over-densities may be conservative, because the potential contamination will be unclustered and so should slightly decrease the significance of any real over-densities, although again we stress that the contamination rate in our emitter sample is expected to be quite low (∼20%) so this should not be a large effect.

2QZ cluster: As can be seen in Figure 5, the over-density in the 2QZ cluster field comprises an apparently filamentary structure connecting at least three of the QSOs at \( z = 2.23 \), as well as an extension of the structure towards the QSO just outside of the field of view to the south west. The three target QSOs lie in weak over-dense regions (δ ∼ 0–1) rather than the local density peaks. The structure around the QSOs contains a 2.9σ density peak from the average density derived in the control field, and it is the second highest peak in the full density map of the 2QZ cluster and the surrounding three control fields (see Figure B1 in Appendix). The local emitter density of this peak is 3.7 times higher than the average density. The highest density peak is located in the west edge of the chip 2. There is a very bright, point-source emitter near to this density peak. This bright emitter may be another luminous AGN at \( z = 2.23 \) as the emission-line luminosity is similar to the target QSOs.

0200+015: There is a local over-density of emitters in the vicinity of the HzRG, with a 3.0σ deviation from the average density. The local emitter density of this peak is 3.3 times higher than the average density. This is one of the highest density peaks in the 0200+015 and the surrounding control fields (see Figure B2). We confirmed that all of the five emitter candidates in this over-density satisfy the \( B-K \) criteria indicating that they are highly likely to be HAEs at \( z = 2.23 \). Four out of the five HAEs in the over-density, including the HzRG, are also observed with our independent MOIRCS data and selected as narrow-band excess sources, supporting the reliability of our sample selection (see Figure 5 and Figure 9). Finally, we obtained optical spectroscopy of the 0200+015-C3-HAE2 using LRIS on Keck, the second brightest HAE in the 0200+015 field. The 0200+015-C3-HAE2 is a member of the over-density and 1.8 arcmin (900 kpc at \( z = 2.23 \) in projection) away from the HzRG. The spectrum confirms that this galaxy is at \( z = 2.235 \). We present the spectrum of this source in Figure 6, which shows strong Lyα, CIV1549 and HeII1640 emissions lines with velocity widths of 2.9σ behind this structure (Shen et al. 2007). However, we could not see any clear Lyα absorption-line nor CIV absorption between \( z = 2.216–2.245 \) in its spectrum.

Figure 6. The one dimensional optical spectrum of the second brightest HAE (0200+015-C3-HAE2) in the 0200+015 field. We see strong emission lines corresponding to Lyα, CIV1549 and HeII1640 which yield a redshift of \( z = 2.235 \), confirming this as an Hα-selected source. The strength of HeII and the velocity widths of FWHM ∼ 1000 km s\(^{-1}\) for these lines indicate that this HAE is a narrow-line AGN. This spectroscopic result confirms that our emitter selection works well to identify Hα emitter at \( z = 2.23 \).

SSA 13: We also find a hint for a local over-density of emitters in the SSA 13 field. The local over-density in the vicinity of the SMG/OFRG concentration and has a 2.9σ deviation from the average density. The local emitter density of this peak is 2.7 times higher than the average density. This is the highest density peak in the SSA 13 and surrounding control fields (see Figure B3). All the SMGs and OFRGs are detected in \( K \)-band and their \( K \)-band magnitudes are consistent with the previous results from Smail et al. (2004). However, none of them are selected as emitter candidates, although we detect four out of the five SMGs or OFRGs in our H\( _2 \)S1 image (see Figure 2). This may be due to the relatively shallow depth of the H\( _2 \)S1 image in SSA 13 (Table 2). For two of the OFRGs in this field the observed H\( \alpha \) equivalent widths have been spectroscopically measured to be \( EW_{\text{obs}} = 65 \) Å and 80 Å (Swinbank et al. 2004). However, a source with \( K \gtrsim 19 \) needs to exhibit a narrow-band excess of \( K – H_2 \)S1 \( \gtrsim 1 \) or \( EW_{\text{obs}} \gtrsim 400 \) Å to comply with our emitter selection criteria. The H\( \alpha \) of the undetected SMG at \( z = 2.247 \) falls near the edge of the H\( _2 \)S1 transmission curve (see Figure 1).

We examine the emission-line morphology of the emitter candidates with \( \Sigma \gtrsim 4 \) (Figure 7). The magnitudes and isophotal areas are measured in the continuum corrected H\( _2 \)S1 images with isophotes determined with ∼2σ surface brightness thresholds of 1.0, 1.4 and \( 2.3 \times 10^{-17} \) ergs\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) for the 2QZ cluster, 0200+015 and SSA 13 fields respectively. While the isophotal areas of most of the emitter candidates are similar to, or somewhat larger than, the sequence of the point sources, several emitters in the 2QZ cluster and 0200+015 fields show...
Figure 7. The continuum corrected $H_2S1$ magnitude versus the continuum corrected $H_2S1$ isophotal area for emitter candidates with $\Sigma \geq 4$. The grey-scale bands represent the point source track without narrow-band excess, while the filled circles indicate those emitters lying on the same chip as the target in each field and the open circles are the emitters in the surrounding control fields. In addition, we highlight the target QSOs and HzRG and label other sources using the naming scheme from Tables A1 and A2. The isophotal areas of the point sources show a characteristic variation with magnitude and so we can conclude those narrow-band excess sources significantly above this envelope are well resolved. In particular, HAE17 in the 2QZ cluster field, shows an isophotal area some three times larger than the locus of point sources in the same magnitude range indicating it is very extended. The magnitudes and area are measured with isophotes determined with $\sim 2\sigma$ surface brightness thresholds of $1.0, 1.4$ and $2.3 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ for the 2QZ cluster, 0200+015 and SSA 13 fields respectively.

Figure 8. False colour image (blue for SCAM $z'$, green for $H_2S1$, and red for $K$) of the brightest QSO, HAE1 (2QZ J100412.8+001257) and the extended HAE candidate, HAE17, in the 2QZ cluster field. The angular separation between the HAE1 and HAE17 is 34 arcsec ($\sim 300$ kpc in projection). HAE17 appears to have an extended emission-line nebula with a spatial extent of $\sim 7.5$ arcsec ($\sim 60$ kpc at $z = 2.23$) and an $H\alpha$ luminosity of $6 \times 10^{42}$ erg s$^{-1}$.

Figure 9. Subaru/MOIRCS thumbnail images of the HAEs in the over-density around the HzRG in the 0200+015 field. The size of the images is $5 \times 5$ arcsec ($\sim 40 \times 40$ kpc). The seeing size of the images is FWHM = 0.5 arcsec. All the four emitter satisfy the $BzK$ criteria, indicating that HAE4 and HAE6 are also likely to be at $z = 2.23$. We see that HAE1, 2, and 4 exhibit extended $H\alpha$ emission on scales of $\sim 3$–5 arcsec (or 25–40 kpc), while HAE6 appears to be compact. The same magnitude range is used to display for the MOIRCS images. The contours show the bright peaks.

significantly larger isophotal areas than expected for point sources.

The giant HAE candidate in the 2QZ field is HAE17, referred to as 2QZC-C1-HAE17 in Table A1, and this has a spatial extent of $\sim 7.5$ arcsec (60 kpc at $z = 2.23$) in our
narrow-band image. This HAE is only 34 arcsec (∼300 kpc) from the brightest target QSO (HAE1) in this region (see Figure 8) and the continuum source associated with HAE1 satisfies the $BzK$ criteria, suggesting that this is likely to be an Hα emission-line nebula at $z = 2.23$. The emission-line nebula has a continuum-corrected H$_\alpha$ S1 magnitude of 19.0 mag in an isophotal aperture with an area of 9.4 arcsec$^2$, corresponding to an emission-line flux of $1.7 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$ or an Hα luminosity of $6 \times 10^{42}$ erg s$^{-1}$. There is no evidence for an optically bright AGN in HAE17 as the continuum source is spatially resolved in the $B$ and $z'$-band images and in addition the HAE does not have any bright radio source with $f_{1.4GHz} > 1$ mJy in the VLA FIRST catalog (Becker, White, & Helfand 1995), suggesting that it is not similar to the extended emission-line nebulae often seen around powerful radio galaxies (e.g. McCarthy 1994), such as MRC 0200+015 (Figure 9). Unfortunately there is no deep X-ray data in this field necessary to further constrain the presence of an obscured AGN in this nebula.

As shown by Figure 7 there are several potentially resolved emitters in the 0200+015 field: the HzRG and the NLAGN, 0200+015-C3-HAE2, as well as 0200+015-C3-HAE4. All show evidence of having larger isophotal areas than expected for point sources with their narrow-band magnitudes. To investigate the morphologies of these HAEs we can make use of the high-quality imaging from MOIRCS in this field. In Figure 9 we show thumbnails of the three resolved HAEs from MOIRCS, as well as a fourth more compact HAE which falls in the image: 0200+015-C3-HAE6. This figure clearly demonstrates the presence of bright Hα emission-line nebulae around the HzRG and the NLAGN, 0200+015-C3-HAE2, with spatial extents of 4–5 arcsec corresponding to $\sim 30–40$ kpc at $z = 2.23$, while 0200+015-C3-HAE4 also exhibits fainter but similarly extended emission-line nebulosity. The K-band morphology of HAE4 also seems extended on 3 arcsec or $\sim 30$ kpc scales, with the Hα emission-line peaking on the outer edge of the K-band structure. These properties of the HAE4 may resemble to galaxies with large disks at $z = 1.4 – 3$ (Labbé et al. 2003). These extended HAEs, along with HAE17 in the 2QZ field, are obviously relatively common and indicate that star formation is occurring over large regions, comparable to the size of massive galaxies at the present day, even at $z = 2.23$. Current surveys of the HAEs in lower density regions at this epoch have turned up few such examples (e.g. Figure 7 and G08) and so it is possible that these extended emission-line nebulae are an environmental signature, as has been found for giant Lyα nebulae (Lyα blobs, e.g. Steidel et al. 2000; Palunas et al. 2004; Matsuda et al. 2004, 2009; Yang et al. 2010).

We can also use the MOIRCS imaging to determine the efficiency of fibre spectrograph surveys of HAEs using instruments such as FMOS on Subaru (Kimura et al. 2010). In Figure 10, we therefore show the growth curves of the emission-line fluxes from two examples of extended and compact HAEs (0200+015-C3-HAE4 and HAE6) as a function of photometric aperture using the MOIRCS continuum corrected H$_\alpha$S1 image. For comparison, we also plot a point spread function (PSF) using a bright star in the MOIRCS H$_\alpha$S1 image. This result suggests that the $\sim 10–40\%$ of the total fluxes are missing in the 3 arcsec diameter aperture used in this work, while $\sim 40–80\%$ could be missed if we measured the flux in a 1.2 arcsec diameter aperture fibre similar to Subaru/FMOS. This suggests that care must be taken to assess the fibre losses for such spectroscopic surveys, even of high-redshift galaxies, as a fraction of the targets may exhibit highly extended emission. However, as Figure 10 demonstrates, in these cases aperture corrections using rest-frame UV continuum images could be employed to correct these losses and should all the recovery of $\sim 80–100\%$ of the total fluxes.

Finally, in Figure 11 we plot the observed K-band magnitudes and equivalent widths of the emitters as a function of the emitter local over-densities (the local densities around each emitters are calculated excluding the source itself). In order to select an homogeneous emitter sample from the three fields, given their different depths, we exclude emitter candidates in the 2QZ cluster and 0200+015 fields below the detection limit in the SSA 13 field ($f < 1 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$). From this combined sample, we also exclude potential AGNs with emission-line fluxes similar to those of target QSOs and HzRG ($f > 7 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$), this then means we can crudely relate the K-band magnitude to a measure of the stellar mass of the galaxies, assuming that all the HAEs have roughly comparable mass-to-light ratios. We therefore use the relation estimated from G08, $\log_{10} M_* \sim -0.4 \times K$(mag) + 18.45, to convert our K-band magnitudes into stellar masses. In a

![Figure 10. Growth curves of the emission-line fluxes of two typical extended and compact HAEs with MOIRCS imaging in the 0200+015 field. The solid curves show fractions of covered fluxes of two representative HAEs: HAE4 (Extended), HAE6 (Compact), and a point spread function (PSF) corresponding to the 0.5 arcsec seeing MOIRCS Hα images. The dashed curves show the fractions of the rest-frame UV continuum in the 1.0 arcsec SCAM B-band images. The total fluxes are measured with a 2.5 arcsec diameter and normalized to unity. The dashed vertical line indicates the 1.5 arcsec radius aperture photometry used in this work. The dotted vertical line shows the 0.6 arcsec radius of fibre of Subaru/FMOS (Kimura et al. 2010). This suggests that the FMOS fibre may miss up to $\sim 40–80\%$ of the total emission-line fluxes from most extended Hα emitters at $z \sim 2$. However, aperture corrections based on the rest-frame UV continuum images should be able to recover most of the fluxes within 20\% uncertainty levels.](image-url)
similar manner, as the Hα luminosity is a good indicator of star-formation rate (Kennicutt 1998), we can use our Hα equivalent width for the HAEs to estimate their specific star formation rate (SSFR). We show both of these inferred properties in Figure 11. We see that both the K-band magnitudes and equivalent widths (or stellar mass and SSFR) of the resulting sample show weak correlations with the local over-density. The Spearman’s rank correlation coefficients are $r_s = -0.21$ (K-band magnitude), and $-0.27$ (equivalent width), respectively, indicating that the sample distributions are consistent with random distributions at 8% (K-band magnitude) and 3% (equivalent width) confidence levels. Thus our observations suggest there is weak evidence that the emitters in over-dense region tend to have smaller SSFR compared to those in under-dense environments, potentially indicating accelerated evolution in the build-up of galaxies in dense regions at $z = 2.23$ (cf. Steidel et al. 2005; Tanaka et al. 2010; Hatch et al. 2011).

5 DISCUSSION AND CONCLUSIONS

We have undertaken a narrow-band imaging survey of three target fields which contain potential signpost of rare over-dense regions with space densities of $\sim 10^{-7} - 10^{-8} \text{Mpc}^{-3}$ and local control fields to assess the significance of any over-densities. Our survey detects 137 emitter candidates in a volume of $2.1 \times 10^7$ comoving Mpc$^3$ at $z = 2.23$ down to limiting Hα fluxes of $\sim 0.5 - 1 \times 10^{-16} \text{ergs}^{-1} \text{cm}^{-2}$ (equivalent to attenuation un-corrected SFR of $\gtrsim 14 - 28 \text{M}_\odot \text{yr}^{-1}$ or a dust-corrected SFR of $\gtrsim 70 - 190 \text{M}_\odot \text{yr}^{-1}$). This is one of the largest HAE samples currently available at $z \gtrsim 2$. Based on supporting optical imaging of these fields, we estimate that at least 80% of these narrow-band excess sources likely correspond to HAEs at $z = 2.23$. We have confirmed the reliability of our sample selection in one field, 0200+015, by using independent H$_2$S1 observations from MOIRCS/Subaru, recovering all four HAEs selected in the overlap area from our WFCAM imaging, and also spectroscopically confirmed that one of the bright emitters in this field is an Hα source at $z = 2.235$.

Wide-field narrow-band Hα survey is one of the most effective routes to map over-dense regions of star-forming galaxies at high redshift. Our analysis of the density distribution of emitters in our survey, using statistical corrections for the blank-field density (including any potential foreground or background contamination) derived from the parallel control fields, indicates the presence of $3 \sigma$ local over-densities in all three of our target fields. In the 2QZ cluster field the over-dense regions of emitters displays a filamentary structure connecting the four target $z = 2.23$ QSOs. This is similar to the large-scale filamentary structure of Lyα emitters found around the SSA22 $z = 3.1$ protocluster (Steidel et al. 1998; Hayashino et al. 2004; Matsuda et al. 2007). Although the over-densities in the vicinities of the QSOs are small ($\delta \sim 0 - 1$), there is the density peak with $\delta \sim 3$ surrounded by these QSOs. These properties may be similar to the large-scale structure found around another QSO cluster at $z = 1.1$ (Tanaka et al. 2000, 2001). In the HzRG and SMG/OFRG fields, there are smaller-scale over-dense regions in the vicinities of the targets, with peak over-densities of $\delta \sim 2$. These structures are comparable, if slightly smaller, than those found in other Hα surveys.
ACKNOWLEDGMENTS

We thank Alastair Edge, Masayuki Akiyama, Tomoki Hayashino and Scott Chapman for useful discussions. We also thank Jae-Woo Kim for providing their UKIDSS/DXS catalog. YM and IRS acknowledge support from STFC. JEG is supported by NSERC. Some of the data reported here were obtained as part of the UKIRT Service Programme. UKIRT is funded by the STFC. The W. M. Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

REFERENCES

Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Bertin, E., Arnouts, S. 1996, A&A, 117, 393
Bertin E., Mellier Y., Radovich M., Missonner G., Didelon P., Morin B., 2002, ASPC, 281, 228
Best P. N., Lehnert M. D., Miley G. K., Röttgering H. J. A., 2003, MNRAS, 343, 1
Blakeslee J. P., et al., 2003, ApJ, 596, L143
Casali M., et al., 2007, A&A, 467, 777
Chapman S. C., Blain A. W., Smail I., Ivison R. J., 2005, ApJ, 622, 772
Chapman S. C., Blain A., Ibata R., Ivison R. J., Smail I., Morrison G., 2009, ApJ, 691, 560
Chen H.-W., Lanzetta K. M., Webb J. K., 2001, ApJ, 556, 158
Cloves R. G., Campusano L. E., 1991, MNRAS, 249, 218
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Crighton N. H. M., et al., 2010, arXiv, arXiv:1006.4385
Croom S. M., Smith R. J., Boyle B. J., Shanks T., Loaring N. S., Miller L., Lewis I. J., 2001, MNRAS, 322, L29
Croom S. M., Smith R. J., Boyle B. J., Shanks T., Miller L., Outram P. J., Loaring N. S., 2004, MNRAS, 349, 1397
Cutri R. M., et al., 2003, 2MASS All Sky Catalog of point sources, The IRSA 2MASS All-Sky Point Source Catalog. NASA/IPAC Infrared Science Archive.

for proto-clusters around HzRGs at z ≥ 2 (e.g. Kurk et al. 2004a; Tanaka et al. 2010; Hatch et al. 2011). In part this may reflect the fact that our survey is ~5–10 times wider but ~5–10 times shallower than these surveys. It is therefore possible that the structures found in this survey are just the tips of more significant, underlying proto-clusters. Future deeper H2S1 imaging observations will more accurately reveal the true over-densities of these structures.

Deep narrow-band imaging also enables us to examine the Hα morphology of emitters, which provides us with information on star-formation activity in high-redshift galaxies during their formation phase and/or on their surrounding circum galactic medium. In the 0200+015 field, our deeper, higher-resolution MOIRCS narrow-band imaging confirms that the Hα emission from three HAEs (including both the HzRG and the newly discovered narrow-line AGN) is significantly extended on scales of 25–40 kpc. We find several examples of such extended HAEs in our target fields, including a striking example in the 2QZ field, suggesting that these are relatively common in high-density regions, with no clear examples in our control field or reported in the field survey of G08. The spatial extent of these systems, ~30–60 kpc, suggests that star formation at z = 2.23 is occurring over regions in these galaxies comparable to the size of the largest galaxies at the present day or large-scale gas outflows are interacting with the surrounding circums galactic medium in over-dense environments. Looking at the Hα luminosity of the most extended example, 6 × 10^{43} erg s^{-1} for HAE17 in the 2QZ field, if we assume Lyα/Hα = 8.75 (case B and no dust extinction, e.g. McCarthy, Elston, & Eisenhardt 1992), then its Lyα luminosity is expected to be 5 × 10^{43} erg s^{-1}, which would make its spatial extent and Lyα luminosity comparable to those of giant Lyα blobs (Matsuda et al. 2011). However, we need spectroscopic follow-up or deeper Hα imaging to confirm that this extended emission-line nebula is real and is the first Lyα blob. More generally, future higher resolution Hα imaging and integral field spectroscopic observations are essential to investigate the star-formation activity and gas dynamics and metallicity of the inter-stellar medium in these spatially-extended emitters to constrain their role in galaxy formation.

REFERENCES
Gómez P. L., et al., 2003, ApJ, 584, 210
Hall P. B., Green R. F., 1998, ApJ, 507, 558
Hatch N. A., Kurk J. D., Pentericci L., Venemans B. P., Kuiper E., Miley G. K., Röttgering H. J. A., 2011, arXiv, arXiv:1103.4364
Hayashi M., et al., 2009, ApJ, 691, 140
Hayashi M., Kodama T., Koyama Y., Tanaka I., Shimasaki K., Okamura S., 2010, MNRAS, 402, 1980
Hayashino T., et al., 2004, AJ, 128, 2073
Hayes M., Schaerer D., Östlin G., 2010, A&A, 509, L5
Hu E. M., McMahon R. G., 1996, Natur, 382, 231
Iwamuro F., et al., 2003, ApJ, 598, 178
Kajisawa M., Kodama T., Tanaka I., Yamada T., Bower R., 2006, MNRAS, 371, 577
Keel W. C., Cohen S. H., Windhorst R. A., Waddington I., 1999, AJ, 118, 2547
Kennicutt R. C., Jr., 1998, ARA&A, 36, 189
Kashikawa N., Kitayama T., Doi M., Misawa T., Komiyama Y., Ota K., 2007, ApJ, 663, 765
Kim J.-W., Edge A. C., Wake D. A., Stott J. P., 2011, ApJ, 719, 1654
Kimura M., et al., 2010, PASJ, 62, 1135
Kodama T., Tanaka I., Kajisawa M., Kurk J., Venemans B., De Breuck C., Vernet J., Lidman C., 2007, MNRAS, 377, 1717
Kurk J. D., et al., 2000, A&A, 358, L1
Kurk J. D., Pentericci L., Röttgering H. J. A., Miley G. K., 2004, A&A, 428, 793
Kurk J. D., Pentericci L., Overzier R. A., Röttgering H. J. A., Miley G. K., 2004, A&A, 428, 817
Kurk J., et al., 2009, A&A, 504, 331
Labbé I., et al., 2003, ApJ, 591, L95
Landolt A. U., 1992, AJ, 104, 340
Large M. I., Mills B. Y., Little A. G., Crawford D. F., Sutton J. M., 1981, MNRAS, 194, 693
Laher R. B., et al., 2009, ApJ, 691, 687
Lewis I., et al., 2002, MNRAS, 334, 673
Lilly S. J., Tresse L., Hammer F., Crampton D., Le Fevre O., 1995, ApJ, 455, 108
Matsuda Y., et al., 2004, AJ, 128, 569
Matsuda Y., et al., 2005, ApJ, 634, L125
Matsuda Y., et al., 2009, MNRAS, 400, L66
Matsuda Y., et al., 2010, MNRAS, 403, L54
Matsuda Y., et al., 2011, MNRAS, 410, L13
McCarthy P. J., Elston R., Eisenhardt P., 1992, ApJ, 387, L29
McCarthy P. J., 1993, ARA&A, 31, 639
Mei S., et al., 2009, ApJ, 690, 42
Miley G. K., et al., 2004, Natur, 427, 47
Miley, G., De Breuck C., 2007, A&A, 475, 67
Miyazaki S., et al., 2002, PASJ, 54, 833
Oke J. B., et al., 1995, PASJ, 47, 375
Ouchi M., et al., 2004, ApJ, 611, 660
Palunas P., Teplitz H. I., Francis P. J., Williger G. M., Woodgate B. E., 2004, ApJ, 602, 545
Pascarelle S. M., Windhorst R. A., Keel W. C., Odewahn S. C., 1996, Natur, 383, 45
Pentericci L., et al., 2000, A&A, 361, L25
Röttgering H. J. A., van Ojik R., Miley G. K., Chambers K. C., van Breugel W. J. M., de Koff S., 1997, A&A, 326, 505
Schlegel D. J., Finkbeiner D. P., Davis M., 1998, ApJ, 500, 525
Shen Y., et al., 2007, AJ, 133, 2222
Smail I., Scharf C. A., Ivison R. J., Stevens J. A., Bower R. G., Dunlop J. S., 2003, ApJ, 599, 86
Smail I., Chapman S. C., Blain A. W., Ivison R. J., 2004, ApJ, 616, 71
Smith J. A., et al., 2002, AJ, 123, 2121
Sobral D., Best P. N., Smail I., Geach J. E., Cirasuolo M., Garn T., Dalton G. B., 2011, MNRAS, 411, 675
Sobral D., Best P. N., Geach J. E., Smail I., Cirasuolo M., Garn T., Dalton G. B., Kurk J., 2010, MNRAS, 404, 1551
Sobral D., et al., 2009, MNRAS, 398, L68
Sobral D., et al., 2009, MNRAS, 398, 75
Swinbank A. M., Smail I., Chapman S. C., Blain A. W., Ivison R. J., Keel W. C., 2004, ApJ, 617, 64
Steidel C. C., Adelberger K. L., Dickinson M., Giavalisco M., Pettini M., Kellogg M., 1999, ApJ, 492, 428
Steidel, C. C., Adelberger, K. L., Shapley, A. E., Pettini, M., Dickinson, M., & Giavalisco, M. 2000, ApJ, 532, 170
Steidel C. C., Adelberger K. L., Shapley A. E., Erb D. K., Reddy N. A., Pettini M., 2005, ApJ, 626, 44
Steidel C. C., Bogosavljević M., Shapley A. E., Kollmeier J. A., Reddy N. A., Erb D. K., Pettini M., 2011, arXiv, arXiv:1101.2204
Stevens J. A., et al., 2003, Natur, 425, 264
Suzuki R., et al., 2008, PASJ, 60, 1347
Tadaki K.-i., Kodama T., Koyama Y., Hayashi M., Tanaka I., Tokoku C., 2010, arXiv, arXiv:1012.4860
Tanaka I., Yamada T., Aragón-Salamanca A., Kodama T., Miyaji T., Ota K., Arimoto N., 2000, ApJ, 528, 123
Tanaka I., Yamada T., Turner E. L., Suto Y., 2001, ApJ, 547, 521
Tanaka I., et al., 2010, arXiv, arXiv:1012.1860
Tanaka M., De Breuck C., Venemans B., Kurk J., 2010, A&A, 518, A18
Thomas D., Maraston C., Bender R., Mendes de Oliveira C., 2005, ApJ, 621, 673
Tran K.-V. H., et al., 2010, ApJ, 719, L126
van der Werf P. P., Koo, L. C., van der Werf P. P., Moorwood A. F. M., Bremer M. N., 2000, A&A, 362, 509
Venemans B. P., et al., 2007, A&A, 461, 823
Wilman R. J., Morris S. L., Jannuzi B. T., Davé R., Shone A. M., 2007, MNRAS, 375, 735
Yagi M., Kashikawa N., Sekiguchi M., Doi M., Yasuda N., Shimasaki K., Okamura S., 2002, AJ, 123, 66
Yang Y., Zabludoff A., Eisenstein D., Davé R., 2010, ApJ, 719, 1654
Young P., Sargent W. L. W., Boksenberg A., 1982, ApJS, 48, 455

APPENDIX A: TABLES AND THUMBNAIL IMAGES OF Hα EMITTER CANDIDATES
APPENDIX B: FULL SKY MAPS OF EMITTERS
Figure A1. WFCAM thumbnail images of the emitter candidates in the 2QZ cluster and surrounding control fields. The size of the images is $10 \times 10$ arcsec$^2$ ($\sim 80 \times 80$ kpc$^2$). The circle in the bottom-left panel shows the size of the 3 arcsec aperture for photometry. The same magnitude range are used to display for all the images.
Table A1. Properties of the emitter candidates in the 2QZ cluster (C1) and the control fields (C2, C3, and C4)

| ID            | Coordinate (J2000) (h:m:s +00:00:00) | H$_{2}$S$_{1}$ (mag) | $K$ (mag) | $\Sigma$ | $EW_{obs}$ (Å) | log $F_{H\alpha}^{a}$ (cgs) | log $L_{H\alpha}^{b}$ (cgs) | SFR$_{H\alpha}^{c}$ | $M_{*}^{d}$ | Note |
|---------------|-------------------------------------|----------------------|-----------|----------|----------------|-----------------------------|-----------------------------|------------------|----------|------|
| 2QZC-C1-HAE1  | 10:04:12.90 +00:12:57.9             | 15.58                | 16.29     | 110.0    | 219            | -14.68                     | 43.88                      | 7289             | 11.9     | QSO  |
| 2QZC-C1-HAE2  | 10:03:39.79 +00:21:10.8             | 16.02                | 16.80     | 79.1     | 255            | -14.82                     | 43.74                      | 4868             | 11.7     | QSO  |
| 2QZC-C1-HAE3  | 10:03:51.58 +00:15:02.1             | 17.03                | 17.95     | 34.5     | 327            | -15.18                     | 43.38                      | 1761             | 11.3     | QSO  |
| 2QZC-C1-HAE4  | 10:03:38.27 +00:18:23.8             | 17.11                | 17.89     | 28.8     | 255            | -15.26                     | 43.30                      | 1414             | 11.3     | ...  |
| 2QZC-C1-HAE5  | 10:03:25.05 +00:09:20.5             | 18.66                | 18.93     | 3.0      | 66             | -16.24                     | 42.33                      | 90               | 10.9     | ...  |
| 2QZC-C1-HAE6  | 10:04:09.08 +00:15:45.9             | 18.80                | 19.12     | 78       | -16.24         | 42.32                      | 88                          | 10.8             | BzK      |
| 2QZC-C1-HAE7  | 10:03:38.19 +00:14:35.2             | 18.97                | 20.95     | 8.5      | 1758           | -15.79                     | 42.77                      | 316              | 10.1     | BzK  |
| 2QZC-C1-HAE8  | 10:03:26.43 +00:13:01.2             | 19.13                | 20.15     | 5.3      | 391            | -15.99                     | 42.57                      | 179              | 10.4     | BzK  |
| 2QZC-C1-HAE9  | 10:03:32.97 +00:10:04.5             | 19.27                | 20.03     | 3.8      | 241            | -16.13                     | 42.43                      | 120              | 10.4     | BzK  |
| 2QZC-C1-HAE10 | 10:04:04.29 +00:14:14.4             | 19.34                | 19.90     | 2.9      | 156            | -16.26                     | 42.30                      | 84               | 10.5     | BzK  |
| 2QZC-C1-HAE11 | 10:03:33.09 +00:21:28.4             | 19.50                | 20.98     | 4.6      | 808            | -16.05                     | 42.51                      | 151              | 10.1     | BzK  |
| 2QZC-C1-HAE12 | 10:03:33.57 +00:21:22.8             | 19.52                | 20.50     | 3.7      | 369            | -16.16                     | 42.41                      | 113              | 10.2     | BzK  |
| 2QZC-C1-HAE13 | 10:03:24.48 +00:10:52.4             | 19.52                | 20.40     | 3.4      | 307            | -16.19                     | 42.38                      | 103              | 10.3     | BzK  |
| 2QZC-C1-HAE14 | 10:03:43.28 +00:11:44.5             | 19.53                | 20.48     | 3.5      | 344            | -16.17                     | 42.39                      | 108              | 10.3     | BzK  |
| 2QZC-C1-HAE15 | 10:03:43.84 +00:14:20.2             | 19.53                | 20.24     | 2.9      | 221            | -16.26                     | 42.31                      | 85               | 10.4     | BzK  |
| 2QZC-C1-HAE16 | 10:03:39.78 +00:11:15.8             | 19.57                | 20.36     | 3.0      | 257            | -16.24                     | 42.32                      | 88               | 10.3     | BzK  |
| 2QZC-C1-HAE17 | 10:04:12.16 +00:13:29.7             | 19.60                | 21.95     | 5.0      | 3460           | -16.02                     | 42.54                      | 165              | 9.7      | BzK  |
| 2QZC-C1-HAE18 | 10:03:27.82 +00:10:58.6             | 19.67                | 21.04     | 3.8      | 682            | -16.14                     | 42.42                      | 118              | 10.0     | BzK  |
| 2QZC-C1-HAE19 | 10:03:24.89 +00:08:31.8             | 19.71                | >22.15    | >4.6     | >4237          | -16.06                     | 42.50                      | 148              | <9.6     | ...  |
| 2QZC-C1-HAE20 | 10:04:16.74 +00:18:33.0             | 19.82                | 21.25     | 3.4      | 745            | -16.19                     | 42.37                      | 102              | 9.9      | ...  |
| 2QZC-C1-HAE21 | 10:04:02.90 +00:18:52.5             | 19.85                | >22.15    | >4.0     | >3167          | -16.12                     | 42.44                      | 124              | <9.6     | ...  |
| 2QZC-C1-HAE22 | 10:03:40.59 +00:10:07.1             | 19.86                | 20.83     | 2.6      | 356            | -16.30                     | 42.26                      | 75               | 10.1     | ...  |

$^{a}$ The H$_{\alpha}$ flux (erg s$^{-1}$ cm$^{-2}$) corrected for 33% [N$_{II}$] contribution to the measured flux.

$^{b}$ The H$_{\alpha}$ luminosity (erg s$^{-1}$).

$^{c}$ The attenuation corrected star-formation rate derived from the H$_{\alpha}$ luminosity (M$_{\odot}$ yr$^{-1}$).

$^{d}$ The stellar mass estimated from the $K$-band magnitude by assuming a constant mass-to-light ratio from Geach et al. (2008).
Table A1. continued

| ID            | Coordinate (J2000) (h:m:s) (d:m:s) | H$_2$S1 (mag) | K (mag) | $\Sigma$ | EW$_{obs}$ (Å) | $log F_{H\alpha}^\text{H}$ (erg s$^{-1}$ cm$^{-2}$) | $log L_{H\alpha}^\text{H}$ (erg s$^{-1}$) | SFR$_{H\alpha}$ | $M^\alpha_\odot$ | Note |
|---------------|-----------------------------------|--------------|--------|---------|--------------|---------------------------------------------|------------------------------------------|----------------|----------|-------|
| 2QZC-C2-HAE1  | 10:05:11.82 +00:14:18.3           | 16.65        | 18.14  | 64.3    | 824          | -14.91                                      | 43.65                                     | 3778           | 11.2     | ...    |
| 2QZC-C2-HAE2  | 10:05:12.69 +00:10:58.7           | 17.91        | 18.20  | 6.3     | 70           | -15.92                                      | 42.64                                     | 219            | 11.2     | ...    |
| 2QZC-C2-HAE3  | 10:05:36.81 +00:14:19.4           | 18.81        | 20.67  | 9.6     | 1469         | -15.73                                      | 42.83                                     | 370            | 10.2     | ...    |
| 2QZC-C2-HAE4  | 10:05:34.17 +00:19:32.4           | 18.92        | 20.58  | 8.3     | 1061         | -15.80                                      | 42.76                                     | 309            | 10.2     | ...    |
| 2QZC-C2-HAE5  | 10:05:15.08 +00:12:01.8           | 19.06        | 19.98  | 5.4     | 331          | -15.99                                      | 42.57                                     | 180            | 10.5     | ...    |
| 2QZC-C2-HAE6  | 10:05:18.63 +00:14:20.9           | 19.25        | 20.14  | 4.3     | 160          | -16.08                                      | 42.48                                     | 139            | 10.4     | ...    |
| 2QZC-C2-HAE7  | 10:05:40.32 +00:11:09.1           | 19.37        | 20.38  | 4.9     | 450          | -16.03                                      | 42.53                                     | 161            | 10.3     | ...    |
| 2QZC-C2-HAE8  | 10:05:24.12 +00:19:39.4           | 19.28        | 20.10  | 4.1     | 276          | -16.11                                      | 42.45                                     | 128            | 10.4     | ...    |
| 2QZC-C2-HAE9  | 10:05:26.89 +00:14:36.4           | 19.38        | 20.20  | 3.1     | 193          | -16.22                                      | 42.34                                     | 93             | 10.4     | ...    |
| 2QZC-C2-HAE10 | 10:05:29.41 +00:19:59.4           | 19.44        | 20.21  | 3.3     | 250          | -16.19                                      | 42.37                                     | 101            | 10.4     | ...    |
| 2QZC-C2-HAE11 | 10:05:15.88 +00:34:37.6           | 19.45        | 20.39  | 3.7     | 331          | -16.15                                      | 42.32                                     | 116            | 10.3     | ...    |
| 2QZC-C2-HAE12 | 10:05:32.07 +00:09:00.4           | 19.45        | 20.00  | 2.5     | 151          | -16.31                                      | 42.25                                     | 72             | 10.5     | ...    |
| 2QZC-C2-HAE13 | 10:05:12.95 +00:09:10.2           | 19.68        | 21.05  | 3.8     | 680          | -16.14                                      | 42.42                                     | 118            | 10.0     | ...    |
| 2QZC-C2-HAE14 | 10:05:14.51 +00:17:36.5           | 19.75        | 21.43  | 3.9     | 1084         | -16.13                                      | 42.43                                     | 121            | 9.9      | ...    |
| 2QZC-C2-HAE15 | 10:05:51.55 +00:13:16.4           | 19.76        | 21.61  | 4.0     | 1436         | -16.12                                      | 42.45                                     | 126            | 9.8      | ...    |
| 2QZC-C2-HAE16 | 10:05:10.98 +00:19:55.6           | 19.87        | 21.66  | 3.6     | 1312         | -16.17                                      | 42.40                                     | 110            | 9.8      | ...    |
| 2QZC-C2-HAE17 | 10:05:18.32 +00:14:21.0           | 19.89        | 21.59  | 3.4     | 1125         | -16.18                                      | 42.38                                     | 104            | 9.8      | ...    |
| 2QZC-C2-HAE18 | 10:05:19.23 +00:15:01.5           | 19.90        | >22.15 | >3.8    | >2862        | >16.14                                      | 42.42                                     | 116            | <9.6     | ...    |

- $a$ The $H\alpha$ flux (erg s$^{-1}$ cm$^{-2}$) corrected for 33% [Nii] contribution to the measured flux.
- $b$ The $H\alpha$ luminosity (erg s$^{-1}$).
- $c$ The attenuation corrected star-formation-rate rate derived from the $H\alpha$ luminosity (M$_\odot$ yr$^{-1}$).
- $d$ The stellar mass estimated from the $K$-band magnitude by assuming a constant mass-to-light ratio from [Geach et al. 2008].
Table A2. Properties of the emitter candidates in the 0200+015 field (C3) and the control fields (C1, C2, and C4)

| ID          | Coordinate (J2000) (h:m:s) | H$_2$S1 (mag) | K (mag) | $\Sigma$ | EW$_{obs}$ (Å) | log $P_{H\alpha}^3$ (erg s$^{-1}$ cm$^{-2}$) | log $P_{H\alpha}^4$ (erg s$^{-1}$ cm$^{-2}$) | SFR$_{H\alpha}^i$ | $M_d^2$ | Note      |
|-------------|-----------------------------|---------------|---------|----------|----------------|-------------------------------------------|-------------------------------------------|------------------|----------|-----------|
| 0200-C3-HAE1 | 2:02:42.99 +01:49:10.8      | 16.48         | 18.30   | 55.9     | 1369          | -14.81                                    | 43.76                                     | 5080             | 11.1     | HzRG      |
| 0200-C3-HAE2 | 2:02:50.22 +01:48:53.3      | 16.57         | 18.01   | 46.5     | 760           | -14.89                                    | 43.68                                     | 4054             | 11.2     | NLAGN     |
| 0200-C3-HAE3 | 2:03:27.68 +01:44:33.2      | 18.19         | 19.43   | 9.6      | 557           | -15.57                                    | 42.99                                     | 589              | 10.7     | HzK       |
| 0200-C3-HAE4 | 2:03:27.36 +01:48:22.2      | 18.47         | 19.50   | 6.7      | 397           | -15.73                                    | 42.84                                     | 378              | 10.6     | HzK       |
| 0200-C3-HAE5 | 2:03:01.04 +01:52:09.9      | 18.35         | 19.70   | 4.2      | 288           | -15.93                                    | 42.63                                     | 212              | 10.6     | HzK       |
| 0200-C3-HAE6 | 2:02:46.98 +01:47:54.2      | 19.08         | 20.69   | 4.8      | 984           | -15.87                                    | 42.69                                     | 254              | 10.2     | HzK       |
| 0200-C3-HAE7 | 2:02:19.37 +01:55:39.8      | 19.13         | 20.13   | 3.6      | 375           | -16.00                                    | 42.56                                     | 175              | 10.4     | HzK       |
| 0200-C3-HAE8 | 2:02:44.55 +01:56:06.4      | 19.18         | 20.23   | 3.5      | 411           | -16.00                                    | 42.56                                     | 174              | 10.4     | HzK       |
| 0200-C3-HAE9 | 2:03:02.81 +01:49:20.5      | 19.35         | 20.15   | 2.6      | 265           | -16.15                                    | 42.42                                     | 116              | 10.4     | HzK       |
| 0200-C3-HAE10| 2:02:51.92 +01:50:02.9      | 19.36         | 20.19   | 2.6      | 280           | -16.14                                    | 42.42                                     | 118              | 10.4     | HzK       |
| 0200-C3-HAE11| 2:02:34.33 +01:44:58.9      | 19.47         | 20.75   | 2.8      | 442           | -16.11                                    | 42.45                                     | 128              | 10.2     | HzK       |

The H$\alpha$ flux ($\text{erg s}^{-1} \text{cm}^{-2}$) corrected for 33% [Nii] contribution to the measured flux.

b The H$\alpha$ luminosity ($\text{erg s}^{-1}$).

c The attenuation corrected star-formation rate derived from the H$\alpha$ luminosity ($\text{M}_\odot \text{yr}^{-1}$).

d The stellar mass estimated from the K-band magnitude by assuming a constant mass-to-light ratio from Geach et al. (2008).
**Figure A2.** WFCAM thumbnail images of the emitter candidates in the 0200+015 and surrounding control fields. The size of the images is $10 \times 10$ arcsec$^2$ ($\sim 80 \times 80$ kpc$^2$). The circle in the bottom-left panel shows the size of the 3 arcsec aperture for photometry. The same magnitude range are used to display for all the images.
Table A3. Properties of the emitter candidates in the SSA 13 (C1) and the control fields (C2, C3, and C4)

| ID            | Coordinate (J2000) (h:m:s) | H$_2$S1 (mag) | K (mag) | $\Sigma$ (Å) | $EW_{\text{obs}}$ ( Å) | $F_{\text{H}\alpha}^a$ (erg s$^{-1}$ cm$^{-2}$) | $L_{\text{H}\alpha}^b$ (erg s$^{-1}$) | SFR$_{\text{H}\alpha}^c$ (M$\odot$ yr$^{-1}$) | $M_\ast^d$ (M$\odot$) | Note   |
|---------------|---------------------------|---------------|---------|---------------|------------------------|---------------------------------------------|-----------------------------------------|----------------------------------------|-----------------|--------|
| SSA 13-C1-HAE1| 13:12:27.80 +42:42:26.6   | 17.76         | 17.99   | 2.6           | 53                     | -15.95                                      | 42.61                                    | 201                      | 11.3            | ...    |
| SSA 13-C1-HAE2| 13:12:36.58 +42:40:02.5   | 18.26         | 19.04   | 4.5           | 254                    | -15.72                                      | 42.84                                    | 387                      | 10.8            | BzK    |
| SSA 13-C1-HAE3| 13:12:42.53 +42:41:56.0   | 18.68         | 19.31   | 2.6           | 187                    | -15.95                                      | 42.61                                    | 201                      | 10.7            | BzK    |
| SSA 13-C1-HAE4| 13:13:07.72 +42:34:41.0   | 18.71         | 19.81   | 3.7           | 445                    | -15.80                                      | 42.76                                    | 304                      | 10.5            | BzK    |
| SSA 13-C1-HAE5| 13:12:10.36 +42:43:10.6   | 18.81         | 19.64   | 2.8           | 279                    | -15.92                                      | 42.64                                    | 218                      | 10.6            | BzK    |
| SSA 13-C1-HAE6| 13:11:59.75 +42:42:53.3   | 18.98         | 20.14   | 3.0           | 490                    | -15.90                                      | 42.66                                    | 231                      | 10.4            | BzK    |
| SSA 13-C2-HAE1| 13:14:44.24 +42:35:13.7   | 18.84         | 19.94   | 3.3           | 445                    | -15.86                                      | 42.70                                    | 261                      | 10.5            | ...    |
| SSA 13-C2-HAE2| 13:15:04.66 +42:39:44.0   | 18.92         | 19.83   | 2.7           | 322                    | -15.94                                      | 42.62                                    | 207                      | 10.5            | ...    |
| SSA 13-C2-HAE3| 13:15:21.66 +42:46:29.0   | 18.97         | 21.11   | 3.9           | 2331                   | -15.78                                      | 42.78                                    | 325                      | 10.0            | ...    |
| SSA 13-C3-HAE1| 13:15:03.25 +43:01:42.6   | 18.15         | 19.28   | 6.2           | 462                    | -15.58                                      | 42.98                                    | 575                      | 10.7            | ...    |
| SSA 13-C3-HAE2| 13:15:15.31 +43:09:52.7   | 18.32         | 18.71   | 2.5           | 100                    | -15.97                                      | 42.59                                    | 190                      | 11.0            | ...    |
| SSA 13-C3-HAE3| 13:15:13.54 +43:08:30.1   | 18.39         | 18.93   | 3.0           | 150                    | -15.89                                      | 42.67                                    | 238                      | 10.9            | ...    |
| SSA 13-C3-HAE4| 13:15:21.67 +43:06:01.3   | 18.49         | 19.61   | 4.6           | 457                    | -15.71                                      | 42.85                                    | 394                      | 10.6            | ...    |
| SSA 13-C3-HAE5| 13:14:22.61 +43:04:44.9   | 18.78         | 19.49   | 2.6           | 219                    | -15.96                                      | 42.61                                    | 197                      | 10.7            | ...    |
| SSA 13-C4-HAE1| 13:12:39.90 +43:12:11.9   | 17.24         | 17.63   | 6.7           | 99                     | -15.55                                      | 43.02                                    | 630                      | 11.4            | ...    |
| SSA 13-C4-HAE2| 13:11:58.12 +43:06:47.3   | 18.24         | 18.71   | 3.1           | 124                    | -15.88                                      | 42.68                                    | 244                      | 11.0            | ...    |
| SSA 13-C4-HAE3| 13:12:26.80 +43:01:46.4   | 18.86         | 19.65   | 2.6           | 260                    | -15.96                                      | 42.61                                    | 199                      | 10.6            | ...    |
| SSA 13-C4-HAE4| 13:12:45.44 +43:13:32.7   | 18.89         | 20.39   | 3.7           | 840                    | -15.80                                      | 42.76                                    | 303                      | 10.3            | ...    |
| SSA 13-C4-HAE5| 13:12:10.09 +43:07:36.8   | 18.89         | 19.94   | 3.0           | 408                    | -15.89                                      | 42.67                                    | 238                      | 10.5            | ...    |
| SSA 13-C4-HAE6| 13:12:22.13 +43:01:34.0   | 18.98         | 19.99   | 2.7           | 382                    | -15.94                                      | 42.63                                    | 210                      | 10.5            | ...    |

 Alexandra et al., 2001

---

*a* The H$_\alpha$ flux (erg s$^{-1}$ cm$^{-2}$) corrected for 33% [N$_\text{II}$] contribution to the measured flux.

*b* The H$_\alpha$ luminosity (erg s$^{-1}$).

*c* The attenuation corrected star-formation rate derived from the H$_\alpha$ luminosity (M$_\odot$ yr$^{-1}$).

*d* The stellar mass estimated from the K-band magnitude by assuming a constant mass-to-light ratio from Geach et al. (2008).

Figure A3. WFCAM thumbnail images of the emitter candidates in the SSA 13 and surrounding control fields. The size of the images is 10 × 10 arcsec$^2$ (∼ 80 × 80 kpc$^2$). The circle in the bottom-left panel shows the size of the 3 arcsec aperture for photometry. The same magnitude range are used to display for all the images.
**Figure B1.** The sky distribution and smoothed density map of emitter candidates in the 2QZ cluster field. The squares indicate the positions of the four target QSOs. The circles indicate the emitter candidates and the size is proportional to the emission-line flux. The thick horizontal bars show the angular scale of 20 comoving Mpc (6.2 Mpc in physical scale) at \( z = 2.23 \). The contours show deviations of local emitter densities from the average densities, from -0.5 to 3 \( \sigma \) with 0.5 \( \sigma \) intervals.
Figure B2. The sky distribution and smoothed density map of emitter candidates the 0200+015 field. The square indicate the positions of the HzRG. The circles indicate the emitter candidates and the size is proportional to the emission-line flux. The thick horizontal bars show the angular scale of 20 comoving Mpc (6.2 Mpc in physical scale) at $z = 2.23$. The contours show deviations of local emitter densities from the average densities, from -0.5 to 3 $\sigma$ with 0.5 $\sigma$ intervals.
Figure B3. The sky distribution and smoothed density map of emitter candidates at $z \sim 2.23$ in the SSA 13 field. The squares indicate the positions of the SMGs and OFRGs. The circles indicate the emitter candidates and the size is proportional to the emission-line flux. The thick horizontal bars show the angular scale of 20 comoving Mpc (6.2 Mpc in physical scale) at $z = 2.23$. The contours show deviations of local emitter densities from the average densities, from $-0.5$ to $3\sigma$ with $0.5\sigma$ intervals.