Discovery of a high-z protocluster with tunable filters: the case of 6C0140+326 at $z = 4.4$

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ABSTRACT

We present the first results obtained using a tunable narrow-band filter in the search for high-z protoclusters. Using the recently commissioned red tunable filter on the Gran Telescopio Canarias, we have searched for Lyα emitters in a 75 arcmin$^2$ field centred on the $z = 4.413$ radio galaxy 6C0140+326. With three different wavelength tunings, we find a total of 27 unique candidate Lyα emitters. The availability of three different wavelength tunings allows us to make estimates of the redshifts for each of the objects. It also allows us to separate a possible protocluster from a structure in the immediate foreground. This division shows that the foreground region contains significantly fewer Lyα emitters. Also, the spatial distribution of the objects in the protocluster field deviates from a random distribution at the 2.5σ level. The observed redshift distribution of the emitters is different from the expected distribution of a blank field at the $\sim 3σ$ level, with the Lyα emitters concentrated near the radio galaxy at $z \geq 4.38$. The 6C0140+326 field is denser by a factor of 9 ± 5 than a blank field, and the number density of Lyα emitters close to the radio galaxy is similar to that of the $z \sim 4.1$ protocluster around TN J1338−1942. We thus conclude that there is an overdensity of Lyα emitters around the radio galaxy 6C0140+326. This is one of few known overdensities at such a high redshift.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: high-redshift – cosmology: observations – early Universe.

1 INTRODUCTION

The identification of the progenitors of local galaxy clusters at $z > 2$ is a difficult task. For the interval $1 < z < 1.5$, galaxy clusters are most often identified by infrared red-sequence searches or observations of the X-ray-emitting intracluster gas and the number of galaxy clusters at these redshifts is growing steadily (e.g. Stanford et al. 1997, Rosati et al. 1999, 2004; Mullis et al. 2005; Stanford et al. 2006; Muzzin et al. 2009; Bielby et al. 2010; Brodwin et al. 2010). Unfortunately, these methods become increasingly less effective when moving beyond $z = 1.5$ as the number of red galaxies decreases and X-ray emission becomes too faint to be easily observed. However, if we wish to understand the role of environment on galaxy evolution and the emergence of a large-scale structure, it is essential to locate and study galaxy clusters at all possible epochs. Recent results have presented the spectroscopic confirmation of galaxy clusters with X-ray emission at $z > 1.5$ (Wilson et al. 2008; Kurk et al. 2009; Henry et al. 2010; Papovich et al. 2010; Tanaka, Finoguenov & Ueda 2010), with the current distance record being the galaxy cluster CLJ1449+0856 at $z \sim 2.07$ presented by Gobat et al. (2011) (but see also Andreon & Huertas-Company 2011). However, this sample of high-z clusters remains small.

Another successful method of identifying galaxy cluster progenitors at $z > 2$ is to search for overdensities of line-emitting galaxies using narrow-band imaging. These searches are often aimed at fields containing high-z radio galaxies (hereafter HzRGs; Miley & De Breuck 2008), since these are thought to have large stellar masses...
of the order of $10^{11} - 10^{12} M_\odot$ (Rocca-Volmerange et al. 2004; Seymour et al. 2007). According to hierarchical galaxy formation, the most massive galaxies form in the densest environments. The massive nature of HzRGs thus indicates that these objects may trace overdensities in the early Universe. In recent years, many studies have focused on finding galaxy overdensities around HzRGs (e.g. Pascarelle et al. 1996; Knopp & Chambers 1997; Pentericci et al. 2000; Kurk et al. 2004a,b; Overzier et al. 2006; Venemans et al. 2007; Overzier et al. 2008; Galametz et al. 2010; Kaifer et al. 2010; Hatch et al. 2011). Since these overdensities show no evidence of X-ray emission (at luminosities $>10^{44}$ erg s$^{-1}$), it is thought that these are forming clusters, not yet dynamically relaxed (Carilli et al. 2002; Overzier et al. 2005). They are therefore often called 'protoclusters'.

However, even though the number of spectroscopically confirmed $z > 2$ HzRGs approaches 200, the fraction of these that have been studied for the presence of galaxy overdensities remains small. This is partly due to the small number of existing narrow-band filters and the fact that the central wavelengths of these existing filters are often based on strong lines at $z = 0$, such as [O iii] $\lambda$5007. This severely limits the redshifts at which protoclusters can be studied and therefore the absolute number of confirmed protoclusters has remained small.

In this paper, we present the results of a pilot study that utilizes tunable narrow-band filters in the search for line-emitting galaxies around the HzRG 6C0140+326 at $z = 4.413$ (Rawlings et al. 1996; De Breuck et al. 2001). Tunable filters (TFs) allow the user to set the central wavelength and width of the narrow-band filter. TFs use two plane–parallel transparent plates coated with films of high reflectivity and low absorption. By separating the two plates by a small distance of the order of a $\mu$m–mm, a cavity is formed which is resonant at a specific wavelength. Constructive interference at the resonant wavelength then causes all the incident light at that wavelength to be transmitted. Changing the separation between the plates then allows the central wavelength or the width of the filter to be adjusted. TFs therefore alleviate the limitations imposed by a small number of available narrow-band filters at fixed wavelengths and are thus ideally suited for searching for protoclusters at a range of redshifts. More information and details concerning TFs can be found in Bland-Hawthorn (1995) and Jones, Shopbell & Bland-Hawthorn (2002).

Similar studies involving the search for line-emitting galaxies around $z \sim 1$ quasars have been successfully performed by Baker et al. (2001) and Barr et al. (2004). An attempt to use this technique at higher redshifts has led to mixed results. In a work by Swinbank et al. (in preparation), a TF study is presented for two radio-loud quasars located at $z \sim 2$ and one radio-quiet quasar at $z \sim 4.5$. The $z \sim 4.5$ field shows evidence for an overdensity, whereas the two $z \sim 2$ fields lack depth and do not allow for strong conclusions. With the advent of a TF instrument at a $8–10$ m class telescope, it has now become possible to obtain sufficiently deep data to efficiently search for Ly$\alpha$ emitters in the environments of HzRGs at arbitrary redshifts $z > 2$.

The paper is organized as follows: in Section 2 we describe the data, its reduction and the object detection. The sample selection and redshift estimation is treated in Section 3 and we discuss the evidence for the presence of an overdensity in Section 4. Finally, conclusions and future outlook are presented in Section 5. Throughout this paper, we use a standard $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$. All magnitudes given in this paper are in the AB magnitude system.

2 DATA

The radio galaxy 6C0140+326 (hereafter 6C0140) was observed for a total of 18 h using the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS) instrument (Cepa et al. 2000, 2003) at the Gran Telescopio Canarias (GTC), La Palma. OSIRIS consists of two 2048 × 4096 pixel Marconi CCDs with a 72 pixel gap between the two CCDs. The observations were done on several dates from 2010 September to 2011 January. The $2 \times 2$ binning mode was used resulting in a pixel scale of $\sim 0.25$ arcsec pixel$^{-1}$ and a total field of view of $\sim 8.7 \times 8.6$ arcmin$^2$. The radio galaxy was positioned near the optical centre, approximately 15 arcsec from the left edge of CCD 2. The individual exposures have been dithered with offsets of approximately 10–12.5 arcsec in right ascension and 2–4 arcsec in declination. The larger offsets in right ascension have been chosen such as to cover the gap of $\sim 8$ arcsec between the two CCDs without losing the radio galaxy in the gap. A full list of details concerning the observations can be found in Table 1.

Broad-band images were obtained in the $r$ and $i$ bands. The narrow-band images were obtained at three different central wavelengths $\lambda_c$. This was done because the central wavelength of the TFs varies across the field of view approximately as $\lambda_c = \lambda_0 \left(1 - 0.0007930\rho^2\right)$, as given in the OSIRIS TF user manual. Here, $\rho$ is the distance to the optical centre of the instrument in arcminutes and $\lambda_0$ is the wavelength at the optical centre. The maximum full width at half-maximum (FWHM) of the TF is 20 Å; therefore, it was necessary to perform several passes with different $\lambda_c$ in order to cover the entire redshift range of a possible protocluster. At $z \sim 4.4$, the Ly$\alpha$ line is shifted to 6580 Å, so the central wavelengths were chosen to be 6565, 6575 and 6585 Å (hereafter TF1, TF2 and TF3 for brevity). Note that the redshift of the radio galaxy ($z = 4.413$) indicates that it falls between TF2 and TF3.

As noted above, the maximum formal width of the TF is 20 Å. However, the shape of the response curve is Lorentzian rather than

| Band | Exposure time (s) | $\lambda_{\text{eff}}$ (Å) | $\Delta \lambda$ (Å) | Seeing (arcsec) | 5σ limiting magnitude |
|------|-----------------|----------------|----------------|-----------------|----------------------|
| $r$ | 2400 | 6417 | 1685 | 0.8 | 25.8 |
| $i$ | 2100 | 7719 | 1483 | 0.8 | 24.8 |
| TF1 | 15680 | 6565 | 31.4 | 0.8 | 25.1 |
| TF2 | 15680 | 6575 | 31.4 | 0.8 | 25.2 |
| TF3 | 13440 | 6585 | 31.4 | 0.8 | 25.1 |
Gaussian and is approximately given by

\[
T = \left(1 + \frac{2(\lambda - \lambda_c)}{\delta \lambda} \right)^{-1},
\]  

with \(\lambda_c\) being the central wavelength and \(\delta \lambda\) the formal FWHM. Due to the shape being Lorentzian, the transmission has relatively extended wings which results in an effective band width that is larger than the formal value for the FWHM by a factor of \(\pi/2\). Thus, the TF tunings have an effective FWHM of \(\sim 31\,\text{Å}\). Taking this into account, our observations probe the redshift range \(4.386 < z < 4.428\) near the optical centre. The true redshift range that is covered is larger due to the variation of the central wavelength across the field. The relevant filter response curves are shown in Fig. 1 together with a night-sky emission-line spectrum. As can be seen, the skyline contamination is relatively mild.

2.1 Data reduction

The reduction of all the data is done using IRAF.\(^1\) The reduction of the broad-band images includes the standard steps of bias subtraction and flat-fielding, where the latter is done using sky flats. To remove further large-scale gradients a superflat is made from the unregistered science images. This superflat is smoothed and the science frames are subsequently divided by the superflat. The flat science images are then registered with simple offsets in the \(x\) and \(y\) directions using the IRAF task XREGISTER and co-added together.

The reduction of the TF images follows the same general outline as that for the broad-band images with two exceptions. The flat-fielding is done with dome flats and an additional step is included which involves the removal of sky rings. As the central wavelength of the TF filter varies across the field, skylines shift in and out of the filter bandpass causing a pattern of alternating bright and faint concentric rings superimposed on the image. These large-scale gradients are of the order of 3–9 times the rms noise in the individual images. The rings are removed by subtracting a smoothed superflat made using the unregistered science exposures. This superflat is created for each exposure individually as the sky level (and therefore the sky rings) varies between different nights and airmasses. The individual frames are subsequently registered and combined. Finally, all fully reduced science images are registered to the same pixel coordinates using the IRAF tasks GEOMAP and GEOREGISTER.

Due to the wavelength variation across the field and the dithering there is a variation in wavelength in each of the individual pixels. This variation is larger near the edge of the field of view. The wavelength assigned to each pixel in the final images is the mean of the wavelengths of the pixel in question in the individual images. This also implies that the effective FWHM of the TF increases when moving away from the optical centre. This effect is strongest in the right ascension direction because the dithering steps are larger in this direction, with a maximum increase of \(\sim 50\) per cent at the very edges of the images.

Flux calibration for both broad- and narrow-band imaging is achieved using standard star observations obtained at the end of each observing block of 1 h. The standard stars used for the TF flux calibration have full spectral energy distributions (SEDs) available allowing flux calibration at the exact wavelength of each of the TF observations. A further independent check of the flux calibration of the TF observations is obtained using the broad-band data. The \(r\) and \(i\) magnitudes of all objects in the science frames with \(19 < r < 23\) are measured. Then, assuming a power-law SED, the magnitudes of these objects at the wavelength of interest are determined. The median zero-points derived with this method deviate by \(-0.1, -0.04\) and \(+0.005\) mag with respect to the standard star zero-points of TF1, TF2 and TF3. The larger deviation for TF1 and TF2 is likely due to the stronger presence of the H\(\alpha\) absorption line at 6563 Å.

The final reduced and co-added TF images show some artefacts of the reduction. The sky ring subtraction is not optimal due to the applied smoothing and therefore a residual ring pattern remains in the final images. Also, the unique properties of the TF lead to pupil ghosts near bright stars. Point-source ghosts, however, are not present in the final TF images. The dithering results in an offset in point-source ghosts opposite to the actual offset. When combining the individual images the point-source ghosts will therefore be removed.

\(^1\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
The rms scatter around $r_3$ curves shown in Fig. 2, however, are calculated for a $\sim r_3(3)$ curve. This is because the TF is based on the colour–magnitude diagrams for each of the three TF tunings. The radio galaxy is denoted by the square symbol. The selection area is depicted here, but is not identified as being an LAE. These objects are denoted by the open circles. Spurious detections are indicated by crosses.

2.2 Source detection and photometry

Object detection and photometry are done using SExtractor (Bertin & Arnouts 1996) in a double-image mode. We create three different catalogues based on each of the three TF tunings. A detection is defined as a minimum of nine adjacent pixels that each exceed the 2$\sigma$ rms noise. Colours are measured using the 2$\sigma$ isophotal apertures determined for the respective selection image, whereas total magnitudes are measured using SExtractor’s MAG_AUTO apertures. Image depth and uncertainties on the photometry are determined using the method of Labbé et al. (2003).

Completeness of the image is measured by adding point sources of a range of magnitudes to the respective images after which source extraction is repeated and the number of recovered objects is assessed. To avoid overcrowding the image we limit the number of objects to 150 per magnitude. This process is repeated 10 times in order to obtain better statistics. We find that the data are 50 per cent complete for point sources down to $r = 26.0$, TF1 = 25.1, TF2 = 25.1 and TF3 = 25.0 mag.

3 RESULTS

3.1 Selection of LAEs

For each of the three TF tunings, a separate sample of Ly$\alpha$ emitters (hereafter LAEs) is selected. The criterion for identifying LAEs is based on the colour–magnitude diagrams of the 6C0140 field as shown in Fig. 2. The galaxies with line emission at the relevant redshift will show an excess of flux in the TF band relative to the $r$-band flux. Most objects do not have emission lines in the TF and thus $r - TF \sim 0$. The rms scatter around $r - TF \sim 0$ at TF $\sim 24$–25 mag is $\sim 0.15$. For an object to be identified as an LAE, we require at least a 5$\sigma$ deviation from $r - TF \sim 0$ and thus that $r - TF > 0.75$.

This excess flux relates to an observed line equivalent width using the relationship

$$EW_{\text{obs}} = \Delta \lambda_0 \frac{\Delta \lambda_{TF}}{10^{-0.4(r-\text{TF})}} \left(1 - 10^{-0.4(r-\text{TF})}\right)$$

from Bunker et al. (1995). Here, $\Delta \lambda$ is the FWHM of the filter in question and $r$ and TF are the measured magnitudes in the broad- and narrow-bands, respectively. The rest-frame equivalent width $EW_0$ is obtained by dividing by $(1 + z)$. Note that this relation does not account for intergalactic medium (IGM) absorption. For LAEs at $z \sim 4.4$, this implies that $EW_{\text{obs}}$ and $EW_0$ are overestimated by a factor of $\sim 1.5$–2. We will return to this correction factor in Section 3.2.

Using equation (3), the colour cut corresponds to approximately $EW_{\text{obs}} > 32$ Å at the optical centre of the field. However, as described in Section 2.1, the dithering results in an effective broadening of the TF when moving away from the optical centre. At the west and east edges of the image, the increase in effective FWHM is $\sim 50$ per cent; thus, the equivalent width cut varies approximately between $EW_{\text{obs}} > 32$ Å and $EW_{\text{obs}} > 48$ Å across the field.

The equivalent width cut used in this work is less stringent than the more commonly used $EW_{\text{obs}} > 80$ Å. This is because the TF is narrower than conventional narrow-band filters, thus, allowing for lower equivalent width objects to be included. We further require that the error parameter $\Sigma > 3$, i.e. the excess flux is at least three times larger than the combined noise of the measured broad- and narrow-band fluxes. Finally, due to the artefacts present in the images, we visually inspect all of the objects that satisfy the above criteria and discard any spurious detections.

As can be seen from Fig. 2, there is a significant number of objects located in the selection area that are not identified as being LAEs. Visual inspection shows that these objects are likely spurious detections because they are often found in the sky-ring residuals, have unphysical shapes, coincide with the pupil ghosts or are located near bright stars and saturation spikes. These objects are therefore not included in the candidate LAE sample. Fig. 3 shows the regions of the image where most of these spurious are located, i.e. the sky rings and the pupil ghosts. Also shown are the locations of bright stars and portions of the image that are affected by vignetting. The bright stars cover $\sim 4$ per cent of the field and therefore do not influence any of the conclusions presented in this work.

Other objects in the selection area may actually have $\Sigma < 3$. Individual values of $\Sigma$ depend on the aperture size for each object. The $\Sigma = 3$ curves shown in Fig. 2, however, are calculated for a fixed aperture size that is taken to be the median aperture size of the LAEs. Thus, individual objects inside the selection area may have $\Sigma < 3$ or vice versa.

For the TF1 filter, which probes exclusively $EW_{\text{obs}} > 32$ Å at the optical centre of the field, the dithering results in an effective broadening of the TF when moving away from the optical centre. At the west and east edges of the image, the increase in effective FWHM is $\sim 50$ per cent; thus, the equivalent width cut varies approximately between $EW_{\text{obs}} > 32$ Å and $EW_{\text{obs}} > 48$ Å across the field.

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For the TF1 filter, which probes exclusively $z < 4.407$, we find a total of 13 candidate LAEs, including the radio galaxy which has $EW_{\text{obs}} = 88.3$ Å. This is smaller than expected as visual
inspection of the TF1 image indicates that the radio galaxy does have a strong narrow-band excess. However, the Lyα emission is extended and coincides with a $z \sim 0.9$ foreground galaxy (Rawlings et al. 1996). This results in strong contamination of the $r$-band flux and therefore the expected narrow-band excess is significantly diminished. To alleviate this problem, we use the $r$ band to define the colour apertures for the radio galaxy. This results in $\text{EW}_{\text{obs}} = 217 \, \text{Å}$ indicating that the presence of the foreground galaxy is indeed important.

The TF2 band at 6575 Å reveals a total of 14 candidate LAEs, including the radio galaxy with $\text{EW}_{\text{obs}} = 470 \, \text{Å}$. Eight of the LAEs have been identified in TF1 as well.

Finally, a total of 17 objects are identified as being candidate LAEs in the TF3 band at 6585 Å. Again, the radio galaxy has been included and its equivalent width is highest in TF3 with $\text{EW}_{\text{obs}} = 578 \, \text{Å}$. Out of the remaining galaxies, eight have not been detected in TF1 or TF2, thus, yielding a total number of 27 unique LAEs (including the radio galaxy) in the field of 6C0140. The properties of the emitters are listed in Tables 2 and 3.

### 3.2 Redshift distribution

Having the multiple tunings of the TF means that the redshift of the LAEs can be constrained to a greater accuracy than with a single narrow-band image. This allows us to investigate the approximate redshift distribution of the candidate LAEs in the field.

In order to obtain the best possible estimated redshifts we model what the effect is of a variety of weighting schemes. We model a simple flat spectrum ($\beta = -2$) with an emission line with rest-frame

Table 2. Coordinates and magnitudes of the detected LAEs. The table is divided in three sections. The objects in the first section are brightest in TF1 and so forth.

| ID | RA     | Dec.   | Detected in | $r$     | TF1   | TF2   | TF3   |
|----|--------|--------|-------------|---------|-------|-------|-------|
| 1  | 01:43:58.2 | +32:49:49.8 | TF1         | 27.2 ± 0.8 | 24.9 ± 0.2 | 25.34 ± 0.3 | 26.3 ± 0.6 |
| 2  | 01:43:44.6 | +32:49:42.6 | TF1         | 23.1 ± 0.1 | 21.87 ± 0.04 | 22.55 ± 0.06 | 22.9 ± 0.1 |
| 3  | 01:43:44 | +32:57:06.0 | TF1, TF2, TF3 | 26.7 ± 0.4 | 24.7 ± 0.1 | 25.0 ± 0.2 | 25.4 ± 0.2 |
| 4  | 01:43:38.9 | +32:53:37.2 | TF1, TF2    | > 27.5 | 24.9 ± 0.2 | 25.2 ± 0.2 | 25.7 ± 0.3 |
| 5  | 01:43:38.3 | +32:49:58.3 | TF1         | 24.6 ± 0.1 | 23.7 ± 0.1 | 23.9 ± 0.1 | 24.2 ± 0.2 |
| 6  | 01:43:35.7 | +32:54:36.0 | TF1         | 25.7 ± 0.2 | 24.7 ± 0.1 | 25.1 ± 0.2 | 25.4 ± 0.3 |
| 7  | 01:43:35.4 | +32:52:11.5 | TF1         | 26.7 ± 0.3 | 25.3 ± 0.2 | 25.8 ± 0.2 | 25.8 ± 0.2 |
| 8  | 01:43:24.8 | +32:54:09.5 | TF1, TF2    | 26.5 ± 0.4 | 24.3 ± 0.1 | 25.4 ± 0.3 | 25.1 ± 0.2 |
| 9  | 01:43:45.9 | +32:53:58.0 | TF1, TF2    | 25.9 ± 0.2 | 24.4 ± 0.1 | 24.4 ± 0.1 | 24.8 ± 0.2 |
| 10 | 01:43:43.3 | +32:52:08.1 | TF2, TF3    | 27.4 ± 1.0 | 25.5 ± 0.3 | 24.6 ± 0.1 | 24.8 ± 0.2 |
| 11 | 01:43:42.1 | +32:55:27.6 | TF2         | 23.7 ± 0.1 | 23.1 ± 0.1 | 22.8 ± 0.1 | 23.1 ± 0.1 |
| 12 | 01:43:41.5 | +32:54:17.2 | TF1, TF2, TF3 | 26.6 ± 0.5 | 25.3 ± 0.3 | 24.3 ± 0.1 | 24.5 ± 0.2 |
| 13 | 01:43:41.4 | +32:53:49.3 | TF1, TF2, TF3 | 25.6 ± 0.3 | 24.6 ± 0.2 | 24.0 ± 0.1 | 24.4 ± 0.1 |
| 14 | 01:43:41.0 | +32:53:48.5 | TF2         | 27.2 ± 0.5 | 26.0 ± 0.3 | 25.7 ± 0.2 | 26.3 ± 0.4 |
| 15 | 01:43:40.2 | +32:55:02.5 | TF2, TF3    | 25.9 ± 0.4 | 24.7 ± 0.2 | 23.9 ± 0.1 | 24.1 ± 0.2 |
| 16 | 01:43:38.0 | +32:49:51.9 | TF1, TF2, TF3 | 22.9 ± 0.1 | 22.19 ± 0.07 | 21.85 ± 0.05 | 22.35 ± 0.08 |
| 17 | 01:43:59.8 | +32:52:16.2 | TF3         | 25.1 ± 0.1 | 25.0 ± 0.2 | 24.8 ± 0.1 | 24.2 ± 0.1 |
| 18 | 01:43:56.4 | +32:54:41.1 | TF2, TF3    | > 27.5 | 26.2 ± 0.3 | 25.7 ± 0.2 | 25.5 ± 0.2 |
| 19 | 01:43:44.8 | +32:56:01.9 | TF3         | 26.7 ± 0.2 | 26.7 ± 0.4 | 27.0 ± 0.5 | 25.3 ± 0.1 |
| 20 | 01:43:43.9 | +32:52:28.6 | TF3         | > 27.5 | 27.5 ± 1.6 | 25.7 ± 0.3 | 24.9 ± 0.1 |
| 21 | 01:43:43.8 | +32:53:49.9 | TF1, TF2, TF3 | 23.65 ± 0.05 | 21.54 ± 0.01 | 20.91 ± 0.01 | 20.75 ± 0.01 |
| 22 | 01:43:38.0 | +32:52:00.9 | TF3         | 25.8 ± 0.1 | 25.8 ± 0.2 | 25.6 ± 0.2 | 24.9 ± 0.1 |
| 23 | 01:43:36.1 | +32:55:00.9 | TF2, TF3    | 24.0 ± 0.1 | 23.8 ± 0.1 | 23.17 ± 0.05 | 23.13 ± 0.05 |
| 24 | 01:43:33.3 | +32:54:09.0 | TF2, TF3    | 25.6 ± 0.2 | 26.1 ± 0.5 | 25.2 ± 0.2 | 24.6 ± 0.1 |
| 25 | 01:43:27.3 | +32:51:32.4 | TF3         | 27.1 ± 0.5 | 27.5 ± 1.4 | 25.7 ± 0.3 | 25.1 ± 0.2 |
| 26 | 01:43:26.6 | +32:52:17.3 | TF3         | 25.7 ± 0.2 | 27.1 ± 0.9 | 25.5 ± 0.2 | 24.8 ± 0.1 |
| 27 | 01:43:25.9 | +32:51:01.8 | TF3         | 26.0 ± 0.2 | 26.4 ± 0.6 | 25.9 ± 0.3 | 25.1 ± 0.2 |

Note. *The radio galaxy. The $r$ band was used as the detection image for this object.*
Table 3. Properties of the detected LAEs.

| ID  | EW_{obs}/EW_0 (Å) | Σ  | F_{Lyα} (erg s^{-1} cm^{-2}) | z_{eff} |
|-----|-------------------|----|-----------------------------|--------|
| 1   | 411/36.2          | 5.2 | 1.4 × 10^{-17}             | 4.310^{0.005} |
| 2   | 84.5/9.1          | 17.9 | 9.0 × 10^{-17}             | 4.337^{0.002} |
| 3   | 209/24.7          | 6.8 | 1.7 × 10^{-17}             | 4.352^{0.003} |
| 4   | >463/ >49.8       | 6.2 | 1.7 × 10^{-17}             | 4.394^{0.003} |
| 5   | 47.6/8.0         | 5.0 | 2.3 × 10^{-17}             | 4.340^{0.004} |
| 6   | 60.3/6.5         | 4.8 | 1.5 × 10^{-17}             | 4.380^{0.003} |
| 7   | 96.9/13.0        | 4.7 | 1.8 × 10^{-17}             | 4.377^{0.005} |
| 8   | 266/29.6          | 8.9 | 2.2 × 10^{-17}             | 4.327^{0.002} |
| 9   | 106/11.7          | 6.7 | 1.9 × 10^{-17}             | 4.404^{0.002} |
| 10  | 552/61.5          | 6.9 | 1.5 × 10^{-17}             | 4.399^{0.002} |
| 11  | 47.5/5.0          | 10.3 | 3.7 × 10^{-17}             | 4.391^{0.001} |
| 12  | 299/31.0          | 7.4 | 2.5 × 10^{-17}             | 4.404^{0.002} |
| 13  | 122/12.9          | 7.2 | 3.7 × 10^{-17}             | 4.404^{0.002} |
| 14  | 120/12.4          | 3.5 | 7.0 × 10^{-18}             | 4.403^{0.006} |
| 15  | 225/23.5          | 7.8 | 4.3 × 10^{-17}             | 4.395^{0.002} |
| 16  | 68.8/7.1          | 12.3 | 1.1 × 10^{-16}             | 4.340^{0.003} |
| 17  | 52.0/4.5          | 5.8 | 1.1 × 10^{-17}             | 4.368^{0.009} |
| 18  | >247/ >25.9       | 5.0 | 1.1 × 10^{-17}             | 4.385^{0.006} |
| 19  | 96.8/10.0         | 6.0 | 5.5 × 10^{-18}             | 4.387^{0.009} |
| 20  | >434/ >45.0       | 6.4 | 1.9 × 10^{-17}             | 4.409^{0.008} |
| 21b | 578/75.0          | 95.5 | 3.6 × 10^{-15}             | 4.412^{0.001} |
| 22  | 47.3/4.5          | 5.0 | 6.9 × 10^{-18}             | 4.394^{0.003} |
| 23  | 45.6/0.6          | 8.7 | 2.8 × 10^{-17}             | 4.383^{0.008} |
| 24  | 65.5/5.9          | 4.8 | 1.6 × 10^{-17}             | 4.388^{0.008} |
| 25  | 300/24.3          | 5.2 | 1.8 × 10^{-17}             | 4.339^{0.005} |
| 26  | 682/5.8           | 5.3 | 9.6 × 10^{-18}             | 4.344^{0.009} |
| 27  | 57.8/5.3          | 3.2 | 1.0 × 10^{-17}             | 4.339^{0.005} |

Note. a EW_{obs} calculated using equation (3), whereas EW_0 is calculated using the method of Venemans et al. (2005). b EW_{obs}, EW_0, Σ and F_{Lyα} for the radio galaxy are calculated on the basis of TF3. The horizontal dividers are the same as in Table 2.

FWHM of 250 or 500 km s^{-1} at certain wavelengths in the range 6555 < λ < 6595 Å. These values for the FWHM are consistent with the values found for 80–90 per cent of LAEs around HzRGs (Venemans et al. 2005, 2007). Absorption by the IGM is taken into account using the Madau (1995) recipe. The modelled spectra are then convolved with the TF response curve as given in equation (2) with λ_{c} = 6565, 6575 and 6585 Å. Using the fluxes in each of the TF tunings, we then derive estimates for the wavelength of the emission line.

The results of this process are shown in Fig. 4. We show two different weighting schemes which can be given in the general form as

\[ \lambda_{eff} = \frac{\sum_{i=1,3} w_i F_i \lambda_i}{\sum_{i=1,3} w_i F_i} . \] (4)

Here, i is TF1, TF2 or TF3, respectively, F_i is the flux in the respective bands, \lambda_i is the central wavelength of the tuning in question at the relevant location in the field and \lambda_{c} is a weighting factor. The black data points represent the case of w_i = 1 for all bands, and the red data points denote the results obtained for

\[ w_i = 2 F_i/\max(TF1, TF2, TF3) . \] (5)

As noted above, the results shown in Fig. 4 are obtained when using the central wavelength values of the optical centre, i.e. \lambda_{TF1} = 6565 Å, \lambda_{TF2} = 6575 Å and \lambda_{TF3} = 6585 Å. However, the wavelength shift acts on each tuning identically and thus the qualitative behaviour shown in Fig. 4 is valid for the entire field, irrespective of the wavelength shift.

We see that the more involved weighting scheme yields better results for almost all redshifts. However, for both weighting schemes the largest discrepancy between the input and output redshifts is at either end of the investigated redshift range. This is to be expected because no data are available to bracket the existing tunings, hence skewing the output redshift towards a central value. The more elaborate weighting scheme alleviates this slightly, but does not yield full agreement. Fig. 4 also shows that the results of the two weighting schemes are fairly robust with respect to the choice of rest-frame FWHM.

The redshifts obtained when using the weights as described in equation (5) are listed in Table 3. Uncertainties have been calculated by varying the measured fluxes according to their respective uncertainties and recalculating \lambda_{eff}. An additional systematic uncertainty was added in quadrature to take into account the limitations of the weighting scheme. This systematic uncertainty is based on the bands in which the object is detected and the offset from the input redshift implied by this as measured from Fig. 4. Finally, to account for the variation in wavelength in each pixel, we add an additional location-dependent uncertainty in quadrature.

None of the LAEs is located at larger redshifts than that of the radio galaxy. This is a selection effect as the highest value of \lambda_{c} is 6585 Å, whereas the Lyα line for 2RG = 4.413 falls at ~6580 Å. Combined with the wavelength shift towards shorter wavelengths across the field this means that the observations are biased towards redshifts lower than the redshift of the radio galaxy. Also, note that the estimated redshift of the radio galaxy is only marginally inconsistent with the spectroscopic redshift of z = 4.413. The slight underestimate with respect to the spectroscopic redshift is possibly due to the fact that we modelled the Lyα line with a maximum FWHM of 500 km s^{-1}, whereas the line is observed to have an

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FWHM of $\sim 1500 \text{ km s}^{-1}$ (Rawlings et al. 1996; De Breuck et al. 2001). A larger linewidth will introduce stronger systematic uncertainties that have not been taken into account in the case of the estimated redshift of the radio galaxy. This may therefore account for the discrepancy.

The redshift estimates can be used to correct the equivalent width values for IGM absorption. As discussed in Section 3.1, equation (3) does not take this into account and underestimates the $r$ continuum flux density. Therefore, EW$_{\text{obs}}$ and EW$_{0}$ are overestimated. The corrections are calculated following the method of Venemans et al. (2005). The resulting corrected rest-frame equivalent widths and corresponding Ly$\alpha$ fluxes are listed in Table 3. The difference between EW$_{\text{obs}}$ and EW$_{0}$ is typically a factor of $\sim 10$. This is consistent with a factor $(1 + z)$ in combination with a factor of $\sim 1.7$. Here the latter factor originates from the fact that a larger portion of the $r$-band flux is absorbed by the IGM compared to the TF flux. The exact factor varies between $\sim 1$ and 2 and depends on the location of the line within the filters and therefore both the redshift of the object and its position in the field.

3.3 Contamination

One of the larger caveats of using narrow-band imaging to select high-z emission-line galaxies is that the final sample may be contaminated by low-z interlopers that have a strong emission line falling in the narrow-band. For our study, the most likely interlopers are [OII] emitters at $z \sim 0.76$ or [OIII] emitters at $z \sim 0.3$. Spectroscopic followup is needed to accurately determine the success rate of the sample presented in this work. However, based on previous spectroscopic studies of $z \sim 4$ narrow-band surveys, the expected number of interlopers in our sample can be estimated and it can be determined whether the results presented here are robust when this is taken into account.

We base our estimate of the success rate on the studies of HzRG TN J1338–1942 (hereafter 1338) by Venemans et al. (2002, 2007), the field study at $z \sim 4.5$ by Dawson et al. (2007) and the study of the LAEs around $z \sim 5.2$ HzRG TN J0924–2201 by Venemans et al. (2004). The success rates in each of these works are fairly similar to each other, ranging from $\sim 75$ per cent to $\sim 95$ per cent depending on whether non-detections are counted as non-confirmations. To investigate the ‘worst case scenario’, we use for our sample the minimum success rate of 75 per cent.

4 DOES 6C0140+326 RESIDE IN A PROTOCLUSTER?

Based on our sample of LAEs, we determine whether there is an overdensity around 6C0140. Due to the wavelength shift across the field, part of the observed field can act as a control field.

In Fig. 5, the spatial distribution of the LAEs is shown. Also shown are two concentric circles indicating the boundaries of two fields: the inner circle of $\sim 12.5 \text{ arcmin}^2$ and the annulus of $\sim 16.3 \text{ arcmin}^2$, respectively. The central field covers the redshifts closest to the radio galaxy and can therefore be considered as a possible protocluster field. The annulus outside this field delimited by the dashed circle probes lower redshifts and is considered to be the field environment. To make the distinction between protocluster and foreground stronger we will only consider TF2- and TF3-detected objects (diamonds and asterisks) in the central field, whereas in the annulus only TF1-detected objects are considered (squares). This selection effectively means that we are limited to $z > 4.38$ in the central field and $z < 4.38$ in the annulus. Furthermore, the width of the TF does not change significantly across the central field and the annulus. Since we only consider TF1 in the annulus, the physical depth of the annulus is thus $\sim 1.3$ times smaller. We thus require the area of the annulus to be larger by the same factor to have the same volume in each of the fields. We find nine objects (excluding the radio galaxy) in the possible protocluster field versus two in the foreground field. This thus indicates that there is a concentration of LAEs near to the radio galaxy.

It is striking that almost all of the objects within the protocluster field are located west of the radio galaxy in a north–south filamentary structure. We test whether the spatial distribution is consistent with a random distribution by applying a two-dimensional Kolmogorov–Smirnov test. There is a probability of 0.01 that the distribution as shown in Fig. 5 is drawn from a random distribution. The distribution is thus different from random at the 2.5σ level. This further indicates that the LAEs are clustered.

Since our control field is not very large, it is susceptible to cosmic variance. To better quantify the overdensity of LAEs around the radio galaxy, we also compare it to the blank field LAEs observed by Dawson et al. (2007). Dawson et al. (2007) presented a differential Lyman$\alpha$ luminosity function for field LAEs with EW$_{\text{obs}} > 80 \text{ Å}$ at $z \sim 4.5$. Fitting a Schechter function to the luminosity function using a fixed value of $\alpha = -1.6$, they find $\Phi' = (1.7 \pm 0.2) \times 10^{-4} \text{ Mpc}^{-3}$ and $L' = (10.9 \pm 3.3) \times 10^{42} \text{ erg s}^{-1}$.

For the 6C0140 field, if we take into account the overlap between the different tunings, the total ‘unique’ volume probed by the protocluster field is 1570 Mpc$^3$. Using the same selection procedure as in Dawson et al. (2007), we find eight emitters (excluding the radio galaxy) in the central field. We calculate the expected number of LAEs in the same field (assuming it is a blank field) using the field luminosity function. The expected number of LAEs is found to be 0.9$^{+0.4}_{-0.3}$, with the uncertainty derived from the uncertainties on $\Phi'$ and $L'$. Here, we use the Lyman$\alpha$ flux of the faintest emitter.
with $EW_{\alpha} > 80$ Å (no. 14) in the protocluster field as lower limit $(7.0 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, this equals $L = 1.4 \times 10^{43}$ erg s$^{-1}$ for the cosmology used by Dawson et al. 2007). We therefore find that the 6C0140 field is denser than a blank field by a factor of 9 $\pm$ 5, where the uncertainty is based on Poisson statistics and the uncertainty on the expected number. Defining galaxy overdensity as $\delta_g = n_{\text{chosen}} / n_{\text{field}} - 1$, we thus find a galaxy overdensity of 8 $\pm$ 5.

Using the overdensity in 6C0140 protocluster field, we can make a rough estimate of the mass contained in this central field. As in Venemans et al. (2005), we use the relation

$$M = \bar{\rho} V \left( 1 + \frac{\delta_g}{b} \right), \quad (6)$$

with $\bar{\rho}$ being the mean density of the Universe, $V$ the comoving volume considered and $b$ the bias parameter which relates the galaxy overdensity to the matter overdensity. Following Steidel et al. (1998) and Shimasaku et al. (2003), we use $b = 3.6$. Using $\bar{\rho} = 3.5 \times 10^{10} M_\odot$ Mpc$^{-3}$ and $V = 1570$ Mpc$^3$ a mass of 0.8–2.9 $\times$ $10^{14}$ M$_\odot$ is found. This is a strict lower limit to the mass of the entire overdensity because the true extent of the protocluster is likely larger than what is indicated by the central protocluster field.

We also determine whether the number density and redshift distribution of LAEs in the 6C0140 field are consistent with that of a $z \sim 4$ protocluster. However, the number of known protoclusters above $z = 4$ is limited. One of the few spectroscopically confirmed cases is the protocluster around 1338 at $z \sim 4.1$. Venemans et al. (2002, 2007) have shown that the field around the radio galaxy is denser in LAEs than a blank field by a factor of $4.8_{-1}^{+2.1}$. Also, Overzier et al. (2006) provided evidence for a relatively large number of Lyman break galaxies (LBGs) in this field.

Venemans et al. (2007) found a total of 54 LAEs with $EW_{\alpha} > 15$ Å in a field of 79.7 arcmin$^2$ around 1338. The narrow-band filter used was a custom filter with $\lambda_c = 6199$ Å and an FWHM of 59 Å (hereafter NB620 for brevity), i.e. approximately twice as wide as the TF tunings used in this study. This difference in width implies that the same emission line, at the respective proper redshifts, will yield a brighter magnitude in the TF. Applying the 50 per cent magnitude limits to the 1338 catalogue will therefore not yield a proper comparison. The recovered Ly$\alpha$ flux is, however, relatively independent of the filter width. We therefore use a cut of $F_{1380} > 7.0 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$. At $z \sim 4.1$, the width of NB620 implies a comoving volume of 12292 Mpc$^3$. Applying the $F_{1380}$ cut, the density of LAEs in the 1383 field is found to be $3.6 \times 10^{-3}$ Mpc$^{-3}$.

Applying the Venemans et al. (2007) selection criteria and excluding the radio galaxy, we find a total of five unique LAEs with $EW_{\alpha} > 15$ Å in the central protocluster field. With a volume of 1570 Mpc$^3$ the density of candidate LAEs is thus $(3.2 \pm 1.4) \times 10^{-3}$ Mpc$^{-3}$, where we used Poisson statistics for the 1σ uncertainty. Thus, the number density of LAEs around 6C0140 is comparable to that in the 1338 protocluster.

The velocity distribution of the spectroscopically confirmed 1338 LAEs have an FWHM of 625 $\pm$ 150 km s$^{-1}$. This is very narrow with respect to local galaxy clusters, but it is in agreement with the trend of decreasing velocity dispersion with increasing redshift (Venemans et al. 2007).

The estimated redshifts of the candidate LAEs are compared to the expected redshift range of the protocluster in the lower panel of Fig. 6. Note that the location of the protocluster region does not coincide with the redshift of the radio galaxy. Instead, we have chosen the redshift of the protocluster such that the number of LAEs consistent with being in the protocluster is maximized. This results in an offset with respect to the radio galaxy of $\Delta z = 0.0084$ or $\Delta v \sim 465$ km s$^{-1}$. This is consistent with what is observed in the 1338 protocluster, where the 1338 radio galaxy is redshifted by 440 km s$^{-1}$ ($\Delta z = 0.0075$) with respect to the majority of the confirmed line emitters. Thus, the radio galaxy does not have to be at the centre of the structure in redshift space. In the situation as shown in Fig. 6 a total of 10 LAEs are consistent with being in the protocluster. This number decreases to 4 when we assume that the protocluster is centred on the radio galaxy. Note that a similar displacement of the radio galaxy with respect to the bulk of the galaxies is seen for the spatial distribution of both the 6C0140 and 1338 fields. Both radio galaxies are located not at the centre of the spatial distribution of emitters, but more at the edge.

Also shown in the upper panel of Fig. 6 is the distribution of the estimated redshifts and a curve that indicates how the effective selection area varies as a function of redshift. The area was estimated by determining the portion of the image for which $\lambda_{\text{low}} < \lambda < \lambda_{\text{high}}$, with $\lambda_{\text{low}}$ and $\lambda_{\text{high}}$ being, respectively, the lower edge of the TF1 tuning and the upper edge of the TF3 tuning. The curve indicates that, based on the effective selection area, we would expect the majority of the objects to have $4.35 < z < 4.39$. However, we find a disproportionately large number of objects at $z > 4.38$, indicating that there is some concentration of LAEs close to the redshift of the radio galaxy. Applying a Kolmogorov–Smirnov test, we determine that there is a probability of $4 \times 10^{-3}$ that the observed distribution is drawn from the expected distribution. The two distributions therefore differ at the $\sim$3σ level.

The top panel of Fig. 6 also shows that we are unable to observe objects that are located at $z > 4.42$. This makes the reported overdensity of 8 $\pm$ 5 difficult to interpret. It may be that the protocluster structure extends beyond $z > 4.42$. If this is the case, then the true
overdensity may differ from the value presented here. Likewise, if the distribution of $\lambda$ of the TFs had been chosen to probe larger redshift values, then such a blueshifted overdensity as found for 6C0140 may be underestimated or even missed altogether.

How do our results hold up when we account for the estimated contamination fraction discussed in Section 3.3? In both the comparison with a blank field and the comparison with a $z \sim 4.1$ protocluster, we found eight emitters in the 6C0140 field. Based on the minimum success rate of 75 per cent we therefore expect two interlopers in our ‘protocluster’ sample. Redoing the comparison with a sample of six emitters, the following results are obtained. In the comparison with the blank field of Dawson et al. (2007), it is found that the 6C0140 field is denser by a factor of 7 ± 4. Thus, the 6C0140 field harbours an overdensity of $\delta_\delta = 6 \pm 4$. The corrected number density in the 6C0140 field is $(2.5 \pm 1.3) \times 10^{-3}$ Mpc$^{-3}$, which is also still in agreement with the 1338 field. The results presented here are therefore valid when contamination is taken into account and we conclude that the 6C0140 field is similarly over-
dense as the 1338 protocluster. This indicates that it may evolve into a massive galaxy cluster at $z = 0$. Furthermore, this result supports the hypothesis that HzRGs are good tracers for galaxy overdensities in the early Universe.

5 CONCLUSIONS AND OUTLOOK

We have presented the first search for high-$z$ protoclusters employing tunable narrow-band filters. This pilot study focuses on the radio galaxy 6C0140+326 at $z \sim 4.4$. Using a combination of three TF tunings, we find a total of 27 unique LAEs in the field around 6C0140+326. Division of the field in a protocluster and a foreground field shows that the protocluster field contains significantly more objects than the foreground field. This indicates that there is a concentration of LAEs near the redshift of the radio galaxy.

A comparison to a blank field shows that the 6C0140 protocluster field contains an overdensity of $8 \pm 5$. The number density in the protocluster field is also comparable to that found in the 1338 protocluster at $z \sim 4.1$. Both these results are robust when taking into account the possible presence of interlopers.

With the availability of three separate TF tunings, we also estimate the redshift distribution of the LAEs. Using results obtained for the 1338 protocluster, we find that 4–10 of the LAEs have redshifts consistent with being in a redshift interval spanned by a typical $z \sim 4$ protocluster. Also, the redshift distribution is different at the 3$\sigma$ level from the expected distribution with a relatively large number of objects at $z > 4.38$. This further strengthens the notion that there is a concentration of LAEs near the radio galaxy.

These results are further evidence that HzRGs pinpoint high-
density regions in the early Universe. The overdensity around 6C0140 may collapse at a later time to form a structure similar to a local galaxy group or cluster. Spectroscopic followup is needed to confirm this result.

We have shown that TFs are an excellent method of confirming the presence of protoclusters around HzRGs at any redshift. At the moment, the wavelength range accessible to the red TF used in this study is limited to $\lambda < 6500$ Å and therefore $z > 4.3$. However, a blue TF covering the wavelength range $\lambda < 6500$ Å will be commissioned in the near future. This will open up the redshift range $2 < z < 4$, which is where most of the known HzRGs are located. Our allocated GTC European Southern Observatory (ESO) large programme can then significantly expand the sample of protoclusters across cosmic time and this would allow an in-depth study of the evolution of these structures.

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