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The discovery of six Lyα emitters near a radio galaxy at $z \sim 5.2$

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Abstract. We present the results of narrow-band and broad-band imaging with the Very Large Telescope* of the field surrounding the radio galaxy TN J0924–2201 at $z = 5.2$. 14 candidate Lyα emitters with an observed equivalent width of at least 124 Å were detected. Spectroscopy of 8 of these objects revealed 6 having redshifts similar to that of the radio galaxy. The density of emitters near the radio galaxy is a factor 3–4 higher than in the field, and comparable to the density of Lyα emitters in the protocluster 1338–1942 at $z = 4.1$. The Lyα emitters near TN J0924–2201 could therefore be part of a structure that will evolve into a 10^{15} $M_\odot$ cluster. These observations confirm that substantial clustering of Lyα emitters occur at $z > 5$ and strengthen the idea that radio galaxies in the early Universe pinpoint regions of high density.

Key words. galaxies: active — galaxies: clusters: general — galaxies: evolution — cosmology: observations — cosmology: early Universe

1. Introduction

One of the most intriguing questions in modern astrophysics concerns the formation of structure in the early Universe (e.g. Bahcall et al. 1997). Although there are viable scenarios for the development of large-scale structure, the epoch and mechanism of the formation of galaxy clusters are still open questions.

The narrow-band imaging technique can efficiently select objects with a strong Lyα line in a narrow redshift range, and is therefore ideal for finding and investigating overdense regions at high redshift (Steidel et al. 2000; Möller & Fynbo 2001; Shimasaku et al. 2003; Palunas et al. 2004). For example, Steidel et al. (2000) used narrow-band imaging to map the extend of a large scale structure at $z \sim 3.09$, discovered in a survey for continuum-selected Lyman-break galaxies. Targeting a strong Lyα absorber in a quasar spectrum, Möller & Fynbo (2001) discovered a filament of Lyα emitters at $z = 3.04$. Shimasaku et al. (2003) found serendipitously a large-scale structure at $z \sim 4.9$ while searching for Lyα emitters in the Subaru Deep Field. They concluded that Lyα emitters must be very biased tracers of mass in the early Universe. Palunas et al. (2004) mapped a known large-scale structure at $z = 2.38$ by imaging the field with a narrow-band filter. They find an inhomogeneous distribution of Lyα emitters containing large voids. These results demonstrate that Mpc-scaled structure had already formed by $z \sim 4.9$.

Narrow-band imaging of distant powerful radio galaxies have shown that these objects are excellent tracers of overdense regions in the early Universe (see reviews by van Breugel et al. 2003; Röttgering et al. 2003) and led to the discovery of several forming clusters (protoclusters) at redshifts ~ 2 (Pascarelle et al. 1996; Pentericci et al. 2000; Kurk et al. 2004), $z \sim 3$ (Le Fèvre et al. 1996; Venemans et al. 2003, 2004) and $z \sim 4$ (Venemans et al. 2002).

An interesting question is to what redshift such large-scale structures can be detected. The most distant known radio galaxy is TN J0924–2201, with a redshift of $z = 5.2$ (van Breugel et al. 1999). In this Letter, we describe

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narrow-band observations of this radio galaxy, and report the discovery of 6 Lyα emitters in the field whose redshifts are close to that of the radio galaxy. [1]

2. Observations and candidate selection

2.1. Imaging observations

To search for candidate Lyα emitters near TN J0924–2201, narrow-band and broad-band (I- and V-band) imaging of the field were carried out during two separate observing sessions in March and April 2002 with the VLT Yepun (UT4), using the FOcal Reducer/ low dispersion Spectrograph 2 (FORS2). The customised narrow-band filter had a FWHM of 89 Å and a central wavelength of 7528 Å, which encompasses the wavelength of the Lyα emission line at $z \sim 5.2$. The images were reduced following standard reduction steps (see Venemans et al. 2004 for more details). The resulting images had effective exposure times of 36860 s (narrow-band) and 9750 s (I-band). The seeing in the final narrow-band, I-band and V-band images was 0.″8, 0.″8 and 1.″05 respectively. The 3 σ limiting magnitudes in an aperture with a 2.″0 diameter were 26.29, 26.65 and 26.80 for the narrow-band, I and V-band respectively. For a Lyα emitter at $z \sim 5.2$ with negligible continuum, the limiting line luminosity is $L_{\rm lim}({\rm Ly}\alpha) = 3 \times 10^{42}$ erg s^{-1} (5 σ). The final images had an area useful for detecting Lyα emitters of 46.8 □′.

2.2. Candidate selection

A total of 3471 objects were detected in the narrow-band image with a signal-to-noise greater than 5 using the program SExtractor (Bertin & Arnouts 1996). For each object, the observed equivalent width was calculated using the method described in Venemans et al. (2004). 24 narrow-band excess objects with an observed equivalent width (EW$_\lambda$) of 124 Å, or, if the excess object is a Lyα emitters at $z \sim 5.19$, a rest-frame equivalent width of EW$_0 > 20$ Å, were located int the field. The V-band image was used to identify low redshift interlopers with an emission line falling in the narrow-band filter. Ten of the 24 objects with EW$_\lambda > 124$ Å were also detected in the V-band with a signal-to-noise greater than 2, and had a $V-I$ colors that were much bluer ($V - I < 1.2$) than expected for a galaxy at $z \sim 5.2$ ($V - I \sim 2.75$, see e.g. Songaila 2004). The remaining 14 candidates were our high priority candidates for follow-up spectroscopy.

2.3. Spectroscopy

For the spectroscopy, a mask was constructed which included the radio galaxy and 8 of the 14 high priority candidate Lyα emitters. This was the maximum number that could be fitted on the mask. The rest of the mask was filled with objects having an excess flux in the narrow-band, but with a lower equivalent width than our selection criterion and/or with a blue $V - I$ color. The observations were carried out on March 3 and 4, 2003 using FORS2 on the VLT Yepun. The total exposure time was 20676 s. For a description of the data reduction process, see Venemans et al. (2004). The rms of the wavelength calibration was always better than 0.25 Å ($\sim$ 10 km s^{-1}) and the flux calibration was accurate to 5%.

3. Results

The radio galaxy and all of the 8 observed candidate Lyα emitters showed an emission line near 7500 Å (Fig. 1). The spectrum of the radio galaxy shows a broad (FWHM $\sim$ 1200 km s^{-1}), asymmetric line. Identification of the emission line with [O II] λ3727, [O III] λ5007 and Hα can be ruled out, because of the lack of confirming lines. The emission is interpreted as Lyα, which is supported by a continuum break across the line (Fig. 1) consistent with the redshift of $z = 5.2$, reported by van Breugel et al. (1999). Two of the 8 candidate Lyα objects are identified with [O III] λ5007 at $z \sim 0.5$, confirmed by the accompanying lines [O III] λ4959 and Hβ. The other six spectra did not show any other emission line in a wavelength range covering more than 3300 Å. The nature of these emission lines is described below.

Of the remaining objects covered by the mask, one is identified as a [O II] λ3727 emitter, also showing [Ne III] λ3869 emission and nine were identified as [O III] λ5007 emitters, confirmed by various lines such as [O III] λ4959, Hβ, Hγ, Hδ, [Ne III] λ3869 and [O II] λ3727. In total 11 [O III] emitters were confirmed in the field, all having a redshift of $z \sim 0.5$.

Remains the identification of the six single emission line object. To distinguish high redshift Lyα emitters from low redshift interlopers various tests can be applied (see Stern et al. 2000, for a review).

Asymmetric line profile A characteristic feature of a high redshift Lyα line is its flux decrement on the blue wing of the Lyα emission (e.g. Dawson et al. 2002). Following Rhoads et al. (2003), the asymmetry of an emission line can be described by the parameters a_λ and a_f. These parameters measure the ratio of the line width and line flux redward and blueward of the line peak. [O II] λ3727 emitters at $z \sim 1$ have typical values of $a_f \approx 0.8$ and $a_\lambda \approx 0.9$, while a sample of high redshift Lyα emitters have $0.9 < a_f < 1.9$ and $0.9 < a_\lambda < 3.1$ (Rhoads et al. 2003, and reference therein). Only two of the emission lines (of emitters # 1388 and # 2704) have a signal-to-noise that is high enough to measure the asymmetry. These two lines are (marginally) asymmetric, an indication that emitters # 1388 and # 2704 are Lyα emitters at $z \sim 5.2$.

Continuum break A high redshift Lyα emitter must have a continuum break across the Lyα line, caused by the Lyα forest between the galaxy and the observer. Madau (1995) predict a break of a factor ~ 5 across the Lyα line at $z \sim 5$. To measure continuum in our spectra, regions that were

[1] Throughout this Letter, magnitudes are in the AB system and a Λ-dominated cosmology with $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$ is assumed.

not effected by strong telluric lines were chosen redward and blueward of the emission line. four had a significant ($> 3\sigma$) detection of continuum emission redward of the emission line, resulting in 2σ lower limits on their flux decrements of 3.6 – 5.3. Such large breaks in the optical are exclusively found in high redshift objects (e.g. Stern et al. 2000). Hammer et al. (1997) showed that [O II] emitters at $0.5 < z < 1.0$ have restframe colors of $U-V < 1.4$, and that objects with restframe $U-V < 1.4$ have a total 4000 Å/ Balmer break of factor < 3. Therefore, the continuum break measured in four of the emitters is most likely caused by neutral H I absorption, and hence these emitters can be identified with Lyα emitters at $z \sim 5.2$.
Equivalent width The emission line object have observed equivalent widths in excess of ~ 250 Å. The two emitters which do not show a convincing line asymmetry and do not show continuum on both redward and blueward of the emission line, have observed equivalent widths of $\mathrm{EW}_\lambda >$ 541 Å. This would correspond to an restframe equivalent width of > 269 Å if the emission line would be [O II] λ3727 at $z \sim 1.0$. Such high [O II] equivalent width emitters are rare. The total number of $z \sim 1$ [O II] emitters expected in our field, derived from Teplitz et al. (2003), is ~ 1. However, the fraction of [O II] emitters with a rest-frame $\mathrm{EW} > 200$ Å is $< 2.5\%$ (Teplitz et al. 2003), which indicate that these two emission line objects are probably not [O II] emitters at $z \sim 1$, but Lyα emitters at $z = 5.2$.

Combining these results, we conclude that these 6 line emitters are almost certainly Lyα emitters at $z = 5.2$.

The extracted Lyα lines were fitted with a Gaussian function to estimate the redshift, line flux and widths (FWHMs). In Table 1 the properties of the Lyα emitters are summarised. The star formation rate (SFR) was calculated from the measured UV continuum fluxes in the images assuming a flat f_ν spectrum and UV flux density to SFR conversion of Madau et al. (1998).

The fraction of foreground contaminants in our sample is estimated to be $2/8 \sim 25\%$. There are 6 additional unconfirmed high priority candidate Lyα emitters in the field. Based on the fraction of contaminants in our sample, ~ 4 of those are expected to be high redshift Lyα emitters.

Interestingly, the six confirmed Lyα emitters have velocities, which cluster within a range of 900 $\mathrm{km\,s^{-1}}$, while the narrow-band filter is ~ 3500 $\mathrm{km\,s^{-1}}$ wide. Also, the radio galaxy is roughly 1000 $\mathrm{km\,s^{-1}}$ away from the central velocity of the emitters. This is different from other $z > 2$ radio galaxy protoclusters, where the radio galaxy has a velocity close to the average velocity of the Lyα emitters (Pentericci et al. 2000; Kurk et al. 2004; Venemans et al. 2002, 2004).

4. Discussion and conclusions

Is there an overdensity of Lyα emitters near TN J0924–2201? To investigate this question, the density of Lyα emitters in our field was compared with the density of blank fields. The search for Lyα emitters at $z \sim 4.79$ in the Subaru Deep Field (SDF, Shimasaku et al. 2004) is com-

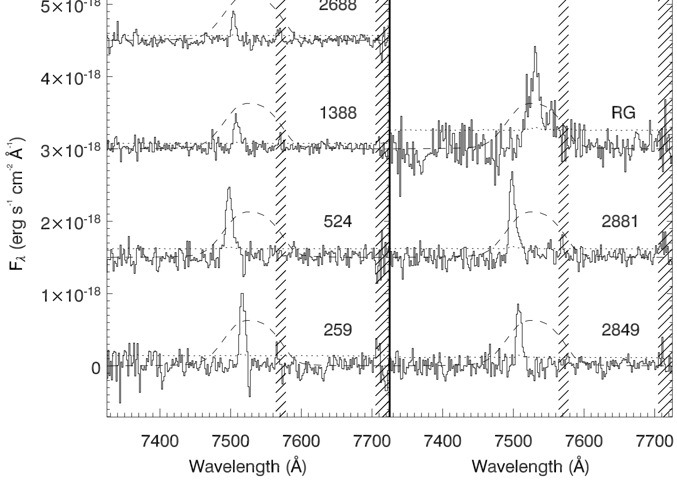

Fig. 1. Part of the spectra of the confirmed Lyα emitters. For clarity the spectra are offset by 1.5×10^{-18} $\mathrm{erg\,s^{-1}\,cm^{-2}}$. The dotted lines indicate the uncertainty in the data, and the dashed line is the transmission curve of the narrow-band filter. The regions in the spectrum where strong telluric skylines dominate are indicated with parallel lines.

parable in depth to our observations ($L_{\mathrm{lim}}(\mathrm{Ly}\alpha) = 3\times10^{42}$ erg $\mathrm{s^{-1}}$ for an emitter at $z = 4.79$ with no continuum). The number density of Lyα emitters at $z \sim 4.79$ in the SDF is $2.1 \pm 0.3 \times 10^{-4}$ $\mathrm{Mpc^{-3}}$ (Shimasaku et al. 2004). Including the radio galaxy, the density of confirmed Lyα emitters in our field is $6.2 \pm 2.3 \times 10^{-4}$ $\mathrm{Mpc^{-3}}$, which is a factor 2.9 ± 1.1 higher than in the SDF. If the four unconfirmed candidate Lyα emitters are included, this factor rises to 4.5 ± 1.5.

Various authors have found that Lyα emitters at high redshift are highly clustered (e.g. Fynbo et al. 2003; Shimasaku et al. 2003; Palunas et al. 2004; Hu et al. 2004). For example, most of the Lyα emitters found at $z = 4.86$ in the SDF are concentrated within a large-scale structure with a radius of $\sim 6'$ (~ 2.5 Mpc) (Shimasaku et al. 2003). It is therefore possible that the Lyα emitters around TN J0924–2201 in the $\sim 7'\times7'$ field of view of FORS2 are located inside such a large-scale structure.

It is interesting to compare the overdensity in this field with the protocluster that was found around the radio galaxy TN J1338–1942 at $z = 4.1$ (Venemans et al. 2002), with an estimated mass of $\sim 10^{15}$ $\mathrm{M_\odot}$. The difference in luminosity distance between $z = 4.1$ and $z = 5.2$ is a factor of 1.32, so the Lyα line at $z = 5.2$ is a factor 1.75 fainter. In this field objects were selected with a (Lyα) line flux of $> 9 \times 10^{-18}$ $\mathrm{erg\,s^{-1}\,cm^{-2}}$. At $z = 4.1$, this corresponds to a limit of $> 1.5 \times 10^{-17}$ $\mathrm{erg\,s^{-1}\,cm^{-2}}$. Of the ~ 26 candidate Lyα emitters in the 1338 field, 10 have a flux in excess of 1.5×10^{-17} $\mathrm{erg\,s^{-1}\,cm^{-2}}$, and were all confirmed to lie at $z = 4.1$ (Venemans et al. 2002). This is the same number as Lyα emitters in the TN J0924–2201 field, which contains six confirmed and four possible Lyα emitters. The Lyα emitters at $z = 5.2$ might therefore be the bright end of a population of star forming galaxies in a protocluster at $z = 5.2$ and this structure could be an

Table 1. Properties of the confirmed Lyα emitters and the radio galaxy.

Object	Position		z	Flux	EW_0	FWHM	SFR
	α_{J2000}	δ_{J2000}		$erg\,s^{-1}\,cm^{-2}$	Å	$km\,s^{-1}$	$M_{\odot}\,yr^{-1}$
259	09 24 07.07	−22 02 09.2	5.1834 ± 0.0002	$8.8 \pm 0.8 \times 10^{-18}$	> 103	< 160	< 3.2
524	09 24 09.41	−22 02 00.5	5.1683 ± 0.0003	$1.2 \pm 0.1 \times 10^{-17}$	97^{+866}_{-21}	323 ± 31	9.1 ± 3.6
1388	09 24 16.68	−22 01 16.9	5.1772 ± 0.0003	$4.1 \pm 0.5 \times 10^{-18}$	59^{+476}_{-14}	187 ± 59	5.1 ± 2.0
2688	09 24 25.67	−22 03 01.1	5.1731 ± 0.0003	$3.1 \pm 0.4 \times 10^{-18}$	> 88	< 151	< 2.9
2849	09 24 24.30	−22 02 30.9	5.1765 ± 0.0003	$8.0 \pm 0.9 \times 10^{-18}$	47^{+785}_{-13}	96 ± 83	6.1 ± 2.7
2881	09 24 23.88	−22 03 44.8	5.1683 ± 0.0005	$1.4 \pm 0.2 \times 10^{-17}$	42^{+45}_{-9}	420 ± 33	13.7 ± 3.4
RG	09 24 19.90	−22 01 42.0	5.1989 ± 0.0006	$2.1 \pm 0.2 \times 10^{-17}$	83^{+148}_{-14}	1138 ± 56	11.6 ± 3.5

early stage in the formation of a 10^{15} $M_{\odot}$ cluster. This should be confirmed by observations of other populations of galaxies (e.g. Lyman break galaxies) in the protocluster.

How important is the role of the radio galaxy in finding such a large-scale structure at $z = 5.2$? It is instructive to calculate how likely it is to find 7 Lyα emitters within the field of view of FORS2. By simulating observations of $z = 4.79$ Lyα emitters the Subaru deep field with FORS2, it was found that the change of finding 7 emitters with FORS2 is only 0.58%. This indicates that distant luminous radio galaxies are preferentially located in high density environments. Since the radio lifetimes (few $\times 10^7$, e.g. Blundell & Rawlings 1999) are small by the standards of cosmic evolution, there must be orders of magnitude more protoclusters in the early Universe without an active radio source.

The overdensity in the field of TN J0924–2201 is the most distant known protocluster. Deep multi-color observations are needed to detect other populations of galaxies in the protocluster and to study the properties of the Lyα emitters in more detail.

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