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Letter to the Editor

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 $z = 5.2$. Fourteen candidate Lyα emitters with a rest-frame equivalent width of >20 Å were detected. Spectroscopy of 8 of these objects showed that 6 have redshifts similar to that of the radio galaxy. The density of emitters at the redshift of the radio galaxy is estimated to be a factor 1.5–6.2 higher than in the field, and comparable to the density of Lyα emitters in radio galaxy protoclusters at z = 4.1, 3.1 and 2.2. The Lyα emitters near TN J0924–2201 could therefore be part of a structure that will evolve into a massive cluster. These observations confirm that substantial clustering of Lyα emitters occurs at $z > 5$ and support the idea that radio galaxies pinpoint high density regions in the early Universe.

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). 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 extent of a large-scale structure at $z \sim 3.09$, discovered in a survey for continuum-selected Lyman-break galaxies. Shimasaku et al. (2003) serendipitously found a large-scale structure at $z \sim 4.9$ while searching for Lyα emitters in the Subaru Deep Field. Their results demonstrate that Mpc-scaled structures have already formed by $z \sim 4.9$ and that Lyα emitters must be very biased tracers of mass in the early Universe.

Narrow-band imaging of distant powerful radio galaxies at z = 2–4 has shown that these objects are often located in rich environments, possibly the early stages in the formation of massive clusters (Pascarelle et al. 1996; Le Fèvre et al. 1996; Pentericci et al. 2000; Venemans et al. 2002, 2003; Kurk et al. 2004). An interesting question is out to which redshift such large-scale structures (protoclusters) 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 broad- and 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 and candidate selection

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 2002 March and April with the VLT Yepun (UT4), using the FOcal Reducer/low dispersion Spectrograph 2 (FORS2). The custom made narrow-band filter had a *FWHM* of 89 Å and a central wavelength of 7528 Å, which encompasses the

⋆ Based on observations carried out at the European Southern Observatory, Paranal, Chile, programs LP167.A-0409 and 70.A-0589.

[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.

wavelength of the Lyα emission line at $z \sim 5.2$. The effective exposure times are 36 860 s (narrow-band), 9750 s (I-band) and 3600 s (V-band). The seeing in the narrow-band, I-band and V-band images is 0.″8, 0.″8 and 1.″05 respectively. The 3σ limiting magnitudes in an aperture with a 2.″0 diameter are 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 5σ limiting line luminosity is $L_{\rm lim}({\rm Ly}\alpha) = 3 \times 10^{42}$ erg s^{-1}. The images have an area useful for detecting Lyα emitters of 46.8 □′.

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 a method that will be described in a future paper (Venemans et al., in preparation). Lyα emitters at $z \sim 5.19$ with a rest-frame equivalent width of $EW_0 > 20$ Å would have an observed equivalent width (EW_λ) of 124 Å. We find 24 such objects in 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 $V - I$ colors that were much bluer ($V-I < 1.2$) than a $V-I$ color of ∼2.75 as expected for a galaxy at $z \sim 5.2$ (e.g. Songaila 2004). The remaining 14 candidates were our high priority candidates for follow-up spectroscopy.

2.2. 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 2003 March 3 and 4 using FORS2 on the VLT Yepun. The mask was observed through the 600RI grism (with a peak efficiency of 87%) with 1.″4 slits. The pixels were 2×2 binned to decrease the readout time and noise, giving a spatial scale of 0.″25 pixel^{-1} and a dispersion of 1.66 Å pixel^{-1}. The total exposure time was 20 676 s. The mean airmass was 1.23 and the seeing in the individual frames varied between 0.″7 and 1.″0, giving a spectral resolution of 185–265 km s^{-1} for point sources. For the wavelength calibration, exposures were taken of He, HgCd, Ar and Ne lamps. The rms of the wavelength calibration was always better than 0.25 Å (∼10 km s^{-1}).

3. Results

The radio galaxy and all of the 8 observed candidate Lyα emitters showed an emission line near 7500 Å. The redshift of the radio galaxy of $z = 5.1989 \pm 0.0006$ is consistent with the redshift of $z = 5.2$, reported by van Breugel et al. (1999).

Two of the 8 candidate Lyα objects (emitters #463 and #559) are identified with [O III] λ5007 at $z \sim 0.5$, confirmed by the accompanying lines [O III] λ4959 and Hβ (Fig. 1 and Table 1). The other six spectra (Fig. 1) did not show any other emission line in a wavelength range covering more than 3300 Å (see Table 1).

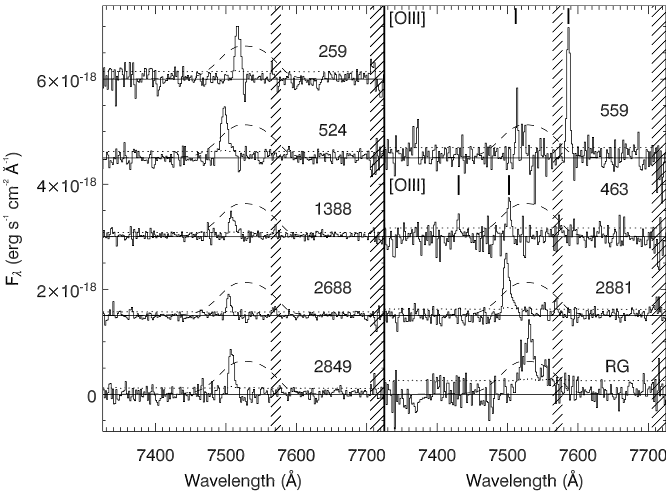

Fig. 1. Part of the spectra of the eight spectroscopically observed high priority emitters and the radio galaxy. For clarity the spectra are offset by 1.5×10^{-18} erg s^{-1} cm^{-2}. The solid lines indicate the zeropoint of the spectra, the dotted lines the 1σ uncertainty in the data, and the dashed lines are the scaled transmission curves of the narrow-band filter. The regions in the spectrum where strong telluric skylines dominate are indicated with hashed lines.

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 the 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 $a_{\rm f}$. These parameters measure the ratio of the line width and line flux redward and blueward of the line peak and depend both on the characteristics of the line (line width, amount of absorption, merged doublet) and on the resolution of the spectrum (Rhoads et al. 2003, and reference therein). Simulations of observed spectra indicate that Gaussian Lyα lines with a *FWHM* of 150–800 km s^{-1} and with the blue side fully absorbed have $a_\lambda = 1.0-1.6$ and $a_{\rm f} = 1.0-1.4$, while [O II] λ3727 emitters have $a_\lambda \approx 0.9$ and $a_{\rm f} = 0.8-0.9$. This is consistent with values found by Rhoads et al. (2003), who measure typical values of $0.9 < a_{\rm f} < 1.9$ and $0.9 < a_\lambda < 3.1$ for a sample of high redshift Lyα emitters and for [O II] emitters at $z \sim 1$ $a_{\rm f} \approx 0.8$ and $a_\lambda \approx 0.9$. Only two of the emission lines (of emitters #1388 and #2881) have a signal-to-noise that is high enough to measure the asymmetry. These two lines are (marginally) asymmetric (with $a_\lambda = 2.0 \pm 0.9 (2.2 \pm 0.6)$ and $a_{\rm f} = 1.7 \pm 0.8 (1.4 \pm 0.6)$ for emitter #1388 (2881)), an indication that emitters #1388 and #2881 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 not effected by strong telluric lines were chosen redward and blueward of

Table 1. Properties of the eight spectroscopically observed high priority candidates and the radio galaxy.

Object	Position		z	Flux	EW_0	$FWHM$	$SFR_{\rm UV}$	$SFR_{\rm Ly\alpha}$
	$\alpha_{\rm J2000}$	$\delta_{\rm J2000}$		erg s^{-1} cm^{-2}	Å	km s^{-1}	$M_\odot$ yr^{-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	208 ± 39	<3.2	3.9 ± 0.7
524	09 24 09.41	−22 02 00.5	5.1683 ± 0.0003	$1.2 \pm 0.1 \times 10^{-17}$	97^{+866}_{-21}	392 ± 25	9.1 ± 3.6	10.4 ± 1.2
1388	09 24 16.68	−22 01 16.9	5.1772 ± 0.0003	$4.1 \pm 0.5 \times 10^{-18}$	59^{+476}_{-14}	295 ± 38	5.1 ± 2.0	3.5 ± 0.5
2688	09 24 25.67	−22 03 01.1	5.1731 ± 0.0003	$3.1 \pm 0.4 \times 10^{-18}$	>88	167 ± 63	<2.9	3.0 ± 0.6
2849	09 24 24.30	−22 02 30.9	5.1765 ± 0.0003	$8.0 \pm 0.9 \times 10^{-18}$	47^{+785}_{-13}	249 ± 32	6.1 ± 2.7	3.3 ± 0.7
2881	09 24 23.88	−22 03 44.8	5.1683 ± 0.0005	$1.4 \pm 0.2 \times 10^{-17}$	42^{+45}_{-9}	479 ± 28	13.7 ± 3.4	6.8 ± 1.1
463[a]	09 24 08.48	−22 00 04.0	0.4983 ± 0.0001	$4.7 \pm 0.7 \times 10^{-18}$	339^{+1966}_{-91}	<200	–	–
559[a]	09 24 09.51	−22 00 18.3	0.51515 ± 0.00003	$1.3 \pm 0.1 \times 10^{-17}$	207^{+160}_{-47}	<70	–	–
RG	09 24 19.90	−22 01 42.0	5.1989 ± 0.0006	$2.1 \pm 0.2 \times 10^{-17}$	83^{+148}_{-14}	1161 ± 55	11.6 ± 3.5	11.4 ± 0.7

[a] [O III] λ5007 emitter.

the emission line. Four spectra had a significant (>3σ) 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 observed [O II] emitters at $0.5 < z < 1.0$ have a total 4000 Å and 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 objects 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 both redward and blueward of the emission line, have observed equivalent widths of $EW_\lambda > 540$ Å. This would correspond to a rest-frame equivalent width of >269 Å if the emission line is [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 $EW > 200$ Å is <2.5% (Teplitz et al. 2003), which indicates that these two emission line objects are probably not [O II] emitters at $z \sim 1$, but Lyα emitters at $z = 5.2$.

Emission line ratios: As mentioned above, no other emission lines were found in the spectra of the emitters. To estimate the likelihood that the emitters are [O II] emitters, we can derive an upper limit on the flux of the [Ne III] λ3869 line and compare that to local emission line galaxies (Fynbo et al. 2001). Stacking the six spectra to increase the signal-to-noise, we find an upper limit on the ratio of [Ne III] line flux over the [O II] flux of flux ([Ne III])/flux([O II]) < 0.07 (2σ). Using the spectrophotometric catalogue of local emission line galaxies of Terlevich et al. (1991), we found that only 5 out of a sample of 151 of the galaxies with both [O II] and [Ne III] lines detected ($5/151 \approx 3\%$) have such a weak neon line. With the estimated number of [O II] emitters (see above), we expect that <1 of our 6 emission line galaxies is an [O II] emitter.

On the basis of these four lines of arguments, 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 IDs correspond to the object's number in the catalogue. To correct for the instrumental broadening, the observed *FWHM* was deconvolved with the resolution. The star formation rates ($SFR_{\rm UV}$ and $SFR_{\rm Ly\alpha}$) were calculated from the measured UV continuum fluxes and line fluxes in the images assuming a flat f_ν spectrum and UV flux density to SFR conversion of Madau et al. (1998).

The velocities of the six confirmed Lyα emitters cluster within a range of 900 km s^{-1} in the rest-frame, while the narrow-band filter is ~3500 km s^{-1} wide. The peak of the Lyα emission of the radio galaxy is roughly 1000 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). This could be due to H I absorption on the Lyα emission line of the radio galaxy. It has been shown that in radio galaxies this absorption can cause a velocity shift of the Lyα line up to 1000 km s^{-1} as compared to other UV emission lines (e.g., Röttgering et al. 1997).

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 $z \sim 0.5$.

4. Discussion and conclusions

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 $z \sim 5.2$ Lyα emitters.

Is there an overdensity of Lyα emitters near TN J0924–2201? To investigate this question, we have to compare the density of Lyα emitters in our field with the density in blank fields. The largest survey near $z \sim 5$

for Lyα emitters is the search for Lyα emitters at $z \sim 4.79$ in the Subaru Deep Field (SDF, Shimasaku et al. 2004). This survey is comparable in depth to our observations ($L_{\rm lim}$(Lyα) $= 3 \times 10^{42}$ erg s^{-1} for an emitter at $z = 4.79$ with no continuum) and the selection criteria applied to identify Lyα emitters are very similar to ours ($EW_\lambda > 80$ Å, Shimasaku et al. 2004). In the SDF, Shimasaku et al. find 51 candidate Lyα emitters in an area of $25' \times 45'$. However, there is no spectroscopic confirmation of these candidates. We therefore conservatively assume that all their candidates are Lyα emitters at $z \sim 4.8$, resulting in a number density of Lyα emitters in the SDF of $2.1 \pm 0.3 \times 10^{-4}$ Mpc^{-3} (Shimasaku et al. 2004). Excluding the radio galaxy, the density of confirmed Lyα emitters in our field is $5.3^{+3.2}_{-2.1} \times 10^{-4}$ Mpc^{-3}, which is a factor $2.5^{+1.6}_{-1.0}$ higher than in the SDF. If the four unconfirmed candidate Lyα emitters are included, this factor rises to $4.2^{+2.0}_{-1.4}$. We used the data from the SDF to estimate the chance of finding 6 or more Lyα emitters in within a single $6\farcm8 \times 6\farcm8$ FORS2 field by counting the number of emitters in randomly placed $6\farcm8 \times 6\farcm8$ apertures. In only 7% of the cases, more than 6 Lyα emitters were found. This further indicates that the TN J0924–2201 field is overdense in Lyα emitters.

Lyα emitters at high redshift show large cosmic variance in their clustering properties (e.g. Shimasaku et al. 2004). Various authors have found that the distribution of Lyα emitters on the sky and/or in redshift space can be very inhomogeneous (e.g. Ouchi et al. 2003; 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 $\sim 6'$ ($\sim$2.5 Mpc, Shimasaku et al. 2003). It is therefore possible that the Lyα emitters around TN J0924–2201 in the $\sim 6\farcm8 \times 6\farcm8$ field of view of FORS2 are located inside such a large-scale structure.

It is interesting to compare the (over)density in this field with the protoclusters that were found around radio galaxies at $z = 4.1, 3.1$ and 2.2, each with at least 20 confirmed protocluster members and estimated masses of $\sim 10^{14}$–10^{15} $M_\odot$ (Pentericci et al. 2000; Kurk et al. 2004; Venemans et al. 2002,Venemans et al. in prep.). In the TN 0924–2201 field objects were selected with a (Lyα) line luminosity of $>3 \times 10^{42}$ erg s^{-1}. At $z = 4.1, 3.1$ and 2.2, this luminosity limit corresponds to a limit of >1.5, 3.1 and 7.0×10^{-17} erg s^{-1} cm^{-2}. The number of candidate (confirmed) emitters with a line brighter than the luminosity limit in the $z = 4.1, 3.1$ and 2.2 protoclusters is 10 (10), 12 (12) and 8 (6) respectively. This is roughly the same number of Lyα emitters as 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 $z = 5.2$, making it the most distant known protocluster. Deep multi-color observations should confirm this by detecting other populations of galaxies (e.g. Lyman break galaxies) in the protocluster.

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