Detecting filaments at z≈3

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Abstract. We present the detection of a filament of Lyα emitting galaxies in front of the quasar Q1205-30 at z=3.04 based on deep narrow band imaging and follow-up spectroscopy obtained at the ESO NTT and VLT. We argue that Lyα selection of high redshift galaxies with relatively modest amounts of observing time allows the detection and redshift measurement of galaxies with sufficiently high space densities that we can start to map out the large scale structure at z≈2-3 directly. Even more interesting is it that a 3D map of the filaments will provide a new cosmological test for the value of the cosmological constant, Ω_Λ.

1 Introduction

For the past few decades computer simulations have been ahead of the observations when it comes to describing the first structures to form at high redshifts. The present consensus of the model builders is that the gas arranges itself in long string–like structures commonly referred to as filaments (see Fig. 1). Density variations along the filaments will lead to formation of lumps of cold, self–shielding HI regions and those regions are identified, in the simulations, as regions of starformation. Because of the high column density of neutral Hydrogen a sightline through such a cloud intersects, they are also identified as strong absorbers known as Damped Lyα Absorbers (DLAs). By poking random sightlines through a virtual universe one may simulate observations, and a given model universe will hence predict a specific correlation between DLA systems and the galaxies hosting the DLAs (e.g. Katz et al. 1996). Comparison to real observations of DLA galaxies (Møller & Warren 1998) has shown that there is very good agreement between observations and simulations. This agreement is encouraging, but it would be of great interest if one could observationally map out the actual filaments. Until now this his been done only at low redshifts (e.g. De Lapparent et al. 1991; Bharadwaj et al. 2000), but never at z>0.1. Knowing the distribution of scalesizes of filaments at different redshifts will help constrain the allowable parameter space of the simulations.

Unfortunately such a map cannot be constructed directly via absorption studies, because there is currently not a sufficiently tight mesh of background z>3 quasars available (e.g. Pichon et al. 2001). The best way to proceed is hence to attempt to find enough centres of starformation to be able to map out filaments by their own light. In order to identify objects to map out filaments one might at first guess that a search for Lyman Break Galaxies (LBGs, Steidel & Hamilton 1992) would be the best procedure. Unfortunately only the very brightest

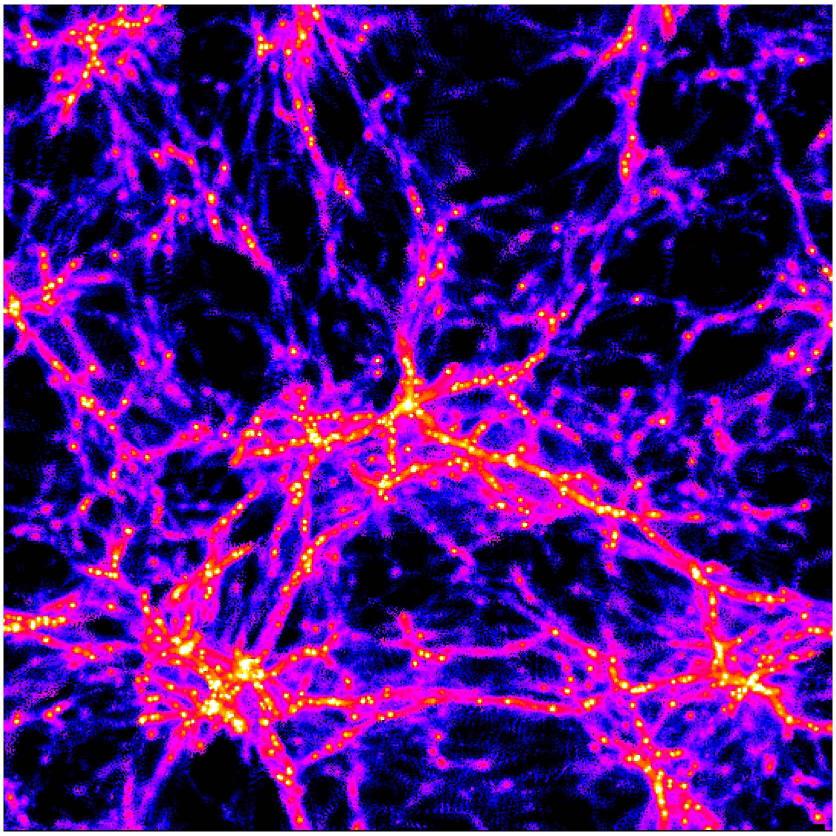

Fig. 1. A hydro simulation of a region of comoving size 12.5/h×12.5/h×1.6/h Mpc^3 at z=3 (courtesy of Tom Theuns, IoA, Cambridge). The image shows the density distribution. The white regions, corresponding to overdensities above 100, are distributed in filamentary structures and in the filament intersections.

galaxies can be found and have their redshifts measured precisely enough with this technique, and such sparse sampling of the filamentary structure does not allow the structures to be seen. However, it has been shown that both DLA galaxies and galaxies selected for their Lyα emission, are sampling the high redshift galaxy population much further down the Luminosity function than do the LBGs, and one will therefore expect a better sampling of the high redshift structure if one uses DLA galaxies and Lyα galaxies (Fynbo, Møller & Warren 1999; Haehnelt et al. 2000). This has recently been independently confirmed, as deep narrow band Lyα imaging in a known overdensity of LBGs revealed about a factor of 10 more candidate Lyα galaxies than LBGs (Steidel et al. 2000).

2 Observations

In February through March 1998 we obtained deep narrow band imaging in a 21Å wide filter tuned to Lyα at z=3.04. The filter was tuned to the wavelength of a strong Lyα absorption line in the spectrum of the QSO (Fig. 2). The data were collected as service observing program at the 3.5-m ESO New Technology Telescope on La Silla, Chile. In total almost 18 hours of narrow band imaging was secured reaching a 5σ flux limit of 1.1×10^{-17} erg s^{-1} cm^{-2} (Fynbo, Thomsen & Møller 2000). We detected six good ($>5\sigma$) and two marginal ($\sim4\sigma$) candidate Lyα emitters in the field of the QSO as well as extended Lyα emission close to the QSO line of sight. In March 2000 we obtained Multi-Object follow-up spectroscopy at the ESO Very Large Telescope using FORS1 on the UT1 unit telescope. We also obtained deep imaging in the B and I bands (reaching B(AB)=26.7 and I(AB)=25.9 at 5σ).

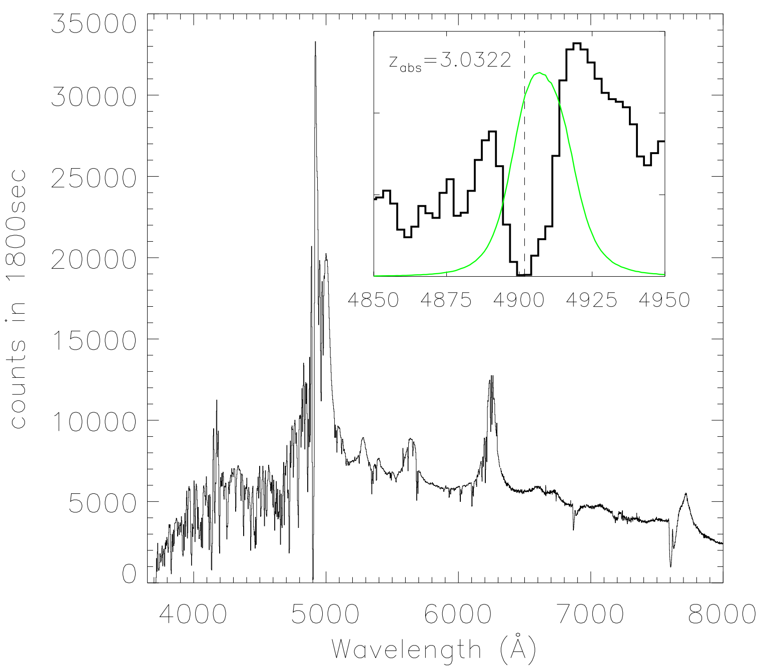

Fig. 2. The spectrum of Q1205-30 obtained at the VLT in March 2000. The insert in the uper right hand corner shows the region of the spectrum around a strong Lyα absorption line z=3.0322. The narrow filter (transmission curve overplotted) was tuned to Lyα at this redshift. The redshift of the background QSO, as measured from the low ionization OI line, is z=3.0473±0.0012.

3 Results

The VLT spectroscopy confirmed (by detecting the Lyα line and at the same time excluding the possibility of low redshift interlopers) all six good candidates and one of the two marginal candidates as Lyα emitters at z=3.04 (Fynbo, Møller & Thomsen 2001). The spectral regions around Lyα for all confirmed candidates are shown in Fig. 3. The spectroscopy of the extended emission close to the QSO line-of-sigt will be presented in a separate paper (Weidinger et al. in preparation).

In Table 1 we present the redshifts and celestial positions for all confirmed Lyα emitters and for the absorber (from Møller & Fynbo 2001).

Table 1. Redshifts and positions of seven Lyα emitters and a Lyα absorber in the field of Q1205–30. The positions are given relative to the quasar coordinates: 12:08:12.7, -30:31:06.10 (J2000.0). The uncertainty on the redshifts is 0.0012 (1σ).

Object	ΔRA (arcsec)	Δdecl. (arcsec)	redshift
S7	-143.3±0.6	41.9±0.2	3.0402
S8	-141.5±0.6	59.7±0.2	3.0398
S9	-124.6±0.5	63.4±0.2	3.0350
S10	-119.9±0.5	59.8±0.2	3.0353
S11	-77.8±0.3	0.9±0.1	3.0312
S12	-43.9±0.2	54.4±0.2	3.0333
S13	68.3±0.3	-52.1±0.2	3.0228
abs	0.0	0.0	3.0322

3.1 Filamentary structure

In Fig. 4 we show the objects plotted in the box defined by the Field of View of the Camera and the redshift depth of the filter for Lyα at z=3. As seen the 7 Lyα emitters (marked with filled symbols) and the absorber (the open symbol) all align in this diagram. If we assume that the redshifts are all solely due to Hubble flow then this implies a real alignment in 3D space e.g. a filamentary spatial distribution of the objects. However, the measured redshift may not be due to Hubble flow alone for mainly two effects : *i)* outflows, and *ii)* peculiar velocities. We now briefly discuss the importance of each of these effects. *Outflows:* In the nearby starburst galaxy NGC1705 the outflow velocity is estimated to be around 80 km s^{-1} (Heckman et al. 2001 and references therein). Outflows of this strength will cause a shift in the redshift measurement which is of the same order as the combined uncertainty from the wavelength calibration and line centroid measurement (corresponding to 90 km s^{-1} at z=3). Outflows will either produce a systematic blueshift of the emission line redshift if the galaxies are opaque (so that we only see the gas moving towards us) or a broadening with no velocity shift of the lines (if the galaxies are transparent and we also see the gas moving away from us). The fact that the absorber, for which the

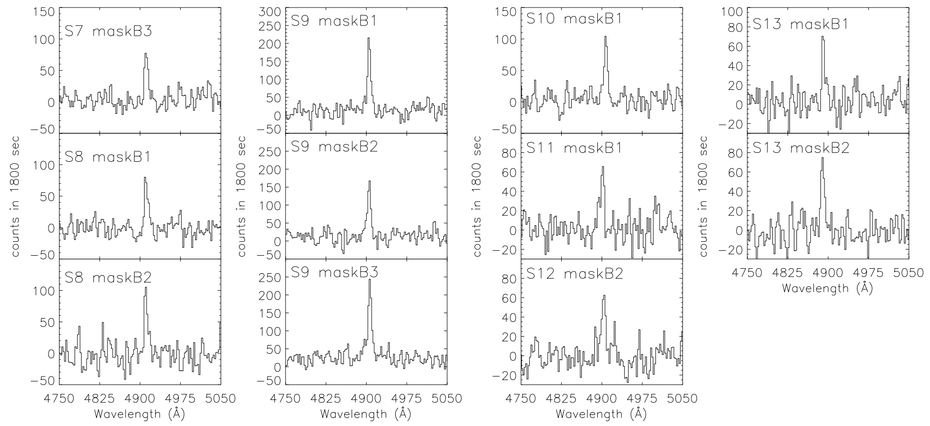

Fig. 3. The spectral regions around the Lyα emission lines for the 7 confirmed Lyα emitters (named S7–S13). For S8, S9, and S13 we show the spectra from several masks. As seen, the presence of emission lines is confirmed for all 7 candidates. By obtaining spectra in a red grism covering the spectral region from 5500Å to 7500Å we exclude the possibility of low redshift interlopers (e.g. OII emiters at z≈0.3, see Fynbo, Møller & Thomsen 2001 for details).

redshift is detemined from the Lyα absorption line, also follows the alignment is an argument against a significant blueshift due to outflows. *Peculiar velocities:* In the local universe (v<4000 km s^{-1}) the $\sigma(\mathrm{v}_{peculiar})$ of peculiar velocities is of the order 200 km s^{-1} (e.g. Branchini et al. 2001). We do not expect this number to be larger at z=3. Furthermore, any peculiar velocities will tend to smear out any underlying filamentary structure, so the fact that we see alignment is an argument against large peculiar velocities. We therefore conclude that the most likely interpretation of Fig. 4 is that we see a redshift z=3 filament.

3.2 Properties of the filament

We can only determine a lower limit to the length of the filament as it seems to extend beyond the volume mapped by our instrumental setup (CCD and filter). Assuming a Hubble constant of 65 km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ we find a coming length (defined as the distance between the two outhermost objects) of 4800 proper kpc. The radius of the minimum cylinder containing all objects is 400 proper kpc. Due to the effect of peculiar and outflow velocities this radius should be considered an upper limit.

The derived properties of filaments are strongly dependend on the assumed cosmology. In particular, since filaments are anchored in the Hubble flow, the observed angular distribution of a sample of filaments will be a function of the assumed cosmology. Therefore, it is in principle possible to use a sample of filaments to obtain an independend constrain on the value of the cosmological constant at z≈3 (Weidinger et al. 2001).

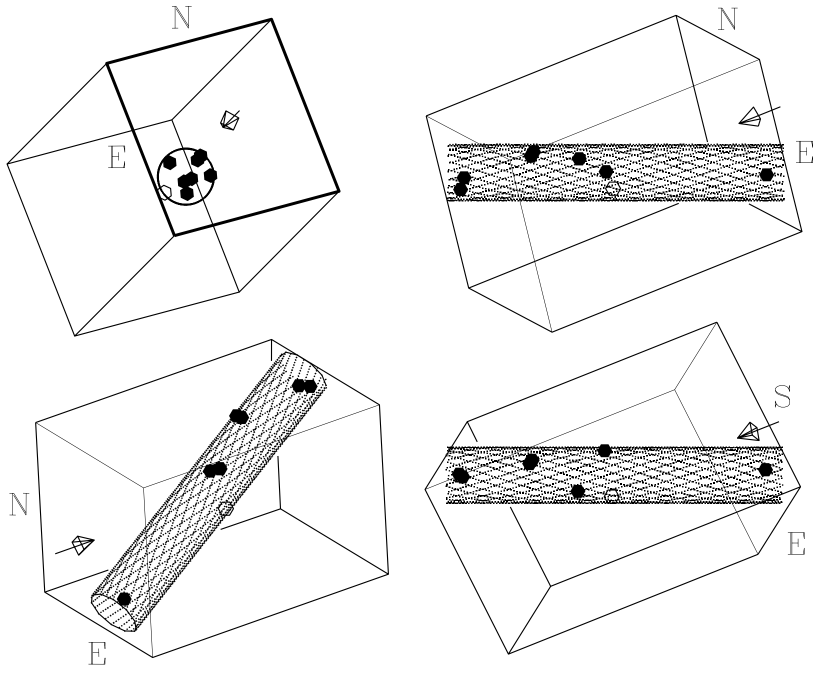

Fig. 4. 3D distribution of the eight objects seen from 4 different viewing–angles. In each of the figures the 3D arrow points in our viewing direction on the sky, and the spiral pattern maps out a cylinder with radius 400 kpc (see Table 1). The box marks the volume of space observed with our narrow–band Lyα filter. **Top left:** Here we have rotated the view to look along the filament. The thick lines mark the front "entrance window" of the box (corresponding to our CCD image). **Top right:** The box is here rotated 90 degrees to the right, hence viewing the filament from the left side compared to the end–on view. **Bottom right:** Same as top right but rotated 90 degrees around the filament to give a view of the filament as seen from "above" the view in top left. **Bottom left:** View from a random angle to give an impression of the 3D structure.

4 Summary and outlook

In order to start mapping out the large scale filamentary structure suggested by numerical simulations directly at high redshift we need cosmic sources that are very numerous rather than rare, very bright light houses such as QSOs or Gamma-Ray Bursters. We have here demonstrated that by reaching flux limits below 1×10^{-17} erg s^{-1} cm^{-2} the density of Lyα emitting galaxies is sufficiently high at z=3 to allow a direct mapping of filamentary structure.

The next logical step is to try to map out larger regions of the z$\approx$2–3 universe with Lyα emitters. Therefore we (Møller, Fynbo, Thomsen, Egholm, Weidinger, Haehnelt, Theuns) have initiated a large area survey for Lyα emitters at z=2 with the 2.56-m Nordic Optical Telescope on La Palma. Furthermore, in a pilot project conducted at the ESO VLT we (here Fynbo, Ledoux, Burud, Leibundgut, Møller and Thomsen) have obtained narrow band observations of two fields around QSO absorbers at z≈3. In the field of the z=2.85 absorber towards Q2138-4427, for which our imaging observations are complete, we reach a detection limit of about 7×10^{-18} erg s^{-1} cm^{-2} and detect 34 candidate Lyα emitters in a 45 $arcmin^2$ field over a redshift range of Δz=0.05. This shows that the density of z=3.04 Lyα emitters in the Q1205-30 field is not unusually high. Follow-up spectroscopic observations of the Q2138-4427 field has not yet been obtained. In the future we hope to map out a large volume with several hundred z=3 Lyα emitters with the VLT.

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