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LETTER

Letter to the Editor

A search for clusters at high redshift

II. A proto cluster around a radio galaxy at $z = 2.16$

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Abstract. VLT[1] spectroscopic observations of Lyα-excess objects in the field of the clumpy radio galaxy 1138–262 at $z = 2.16$ have led to the discovery of 14 galaxies and one QSO at approximately the same distance as the radio galaxy. All galaxies have redshifts in the range 2.16±0.02, centered around the redshift of the radio galaxy, and are within a projected physical distance of 1.5 Mpc from it. The velocity distribution suggests that there are two galaxy subgroups having velocity dispersions of $\sim 500\,\mathrm{km\,s^{-1}}$ and $\sim 300\,\mathrm{km\,s^{-1}}$ and a relative velocity of $1800\,\mathrm{km\,s^{-1}}$. If these are virialized structures, the estimated dynamical masses for the subgroups are $\sim$9 and $\sim 3 \times 10^{13}$ $M_{\odot}$ respectively, implying a total mass for the structure of more than 10^{14} $M_{\odot}$. The new observations, together with previous results, suggest that the structure of galaxies around 1138–262 is likely to be a forming cluster.

Key words: galaxies: active – galaxies: clusters: general – galaxies: evolution – cosmology: observations – cosmology: early Universe – cosmology: large-scale structure of Universe

1. Introduction

One of the most intriguing questions in modern astrophysics concerns the formation of large scale structure in the early Universe (e.g. Bahcall et al. 1997). Although various scenarios have been developed within the context of modern cosmological models, the epoch and mechanism of the formation of galaxy clusters are still open questions.

Despite several tentative identifications of clusters and groups at high redshift (e.g. Keel et al. 1999; Campos et al. 1999; Pascarelle et al. 1998), there is yet no solid identification of collapsed clusters or groups at redshifts above 1.5. Recently Steidel et al. (2000) reported the discovery of a significant overdensity of galaxies at $z \sim 3.1$ and pointed out its possible association with a quasar.

During the last few years evidence that distant radio galaxies may be located in over-dense environments has mounted (e.g. Röttgering et al. 1999). Because such objects can be detected out to $z > 5$, we have begun a programme to survey their surroundings for galaxy overdensities. As a good candidate for a pilot project we selected the powerful radio galaxy 1138–262 from a compendium of more than 150 $z > 2$ known radio galaxies, for several reasons, including (i) its extremely clumpy optical morphology and large size that resembles simulations of forming massive galaxies (Pentericci et al. 1998); (ii) its extreme Faraday rotation and distorted radio morphology indicating a dense magnetized surrounding gas and (iii) its detection of possibly extended X-ray emission (Carilli et al. 1998). Deep VLT narrow and broad band imaging of 1138–262, carried out during April 1999 (Kurk et al. 2000, hereafter Paper I), revealed 50 candidate Lyα emitters in a $7' \times 7'$ field around the radio source. The derived luminosity function indicated a possible overdensity of galaxies in this field, expecially considering that a large fraction of the starburst galaxies and the more passive elliptical galaxies would not show Lyα emission. Therefore these observations strongly suggested the presence of a forming cluster around 1138–262. Here we report on follow up spectroscopic observations of these cluster candidates.[2]

2. Selection, observations and data reduction

The observations were carried out on March 1, 2 and April 7, 2000 with the 8.2m VLT Antu telescope (UT1), using the

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[1] Based on observations carried out at the European Southern Observatory, Paranal, Chile, programme 64.O-0134.

[2] Throughout this paper we assume a Hubble constant of $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and a deceleration parameter of $q_0 = 0.5$

FORS1 imaging spectrograph in the multi-object spectroscopic (MOS) mode with standard resolution, giving a pixel scale of 0.2″ and a field of view of 6.8′× 6.8′. The first two nights were photometric, the third was not. The spectra were obtained with the 600B grism, using a wavelength range from 3450 to 5900 Å, depending on the position of the slit in the set–up and with a dispersion of 1.2 Å pixel^{-1}.

Three different set–ups were used, each with 19 slits. We have chosen a slit size of 1″, which gives a resolution of ~ 5 Å corresponding to about 400 km s^{-1} at $z = 2.16$. The MOS set–up constrains the choice of targets. Therefore, to allow a wider choice of targets, we included in our list of candidate Lyα emitters not only the 50 objects selected in Paper I, that had equivalent width (EQW) ≥ 65 Å (corresponding to a rest-frame EQW of 20 Å) and a narrow band flux density $\geq 2 \times 10^{-19}$ ergs s^{-1} cm^{-2} Å^{-1}, but also those with fluxes below this limit. The total number of possible targets was then 75 instead of 50.

Of the 57 slits available, we placed 2 on different components of the central radio galaxy, and 46 on candidate Lyα emitters (3 of which were observed twice). Of the remaining 9 slits, 3 (one in each set–up) were placed on relatively bright stars to check that the slits were positioned properly, and 6 were placed on additional objects, with EQW just below the cutoff adopted in Paper I. The observations were divided into multiple one hour exposures to facilitate removal of cosmic-ray effects from the final image. The first set–up was observed for a total of 6 hours, the second for 5.5 hours, and the third for 4 hours. All observations were carried out at airmass less than 1.5.

The data were reduced using standard IRAF procedures: after bias subtraction and flat field removal, for each slit the background was subtracted from the data avoiding regions where the spectrum was visible. A relative flux calibration was obtained from a longslit observation with the 600B grating of the spectrophotometric standard star GD108 (Oke 1990). Wavelength calibration was obtained from exposures of He and HgCd arc-lamps taken on the afternoon before the observations. The accuracy of the wavelength calibration was better than 0.2 Å. One–dimensional spectra were extracted for all objects, using aperture sizes which included all the emission.

3. Results

For 15 candidates we obtained a clear detection of an emission line, which we identify as Lyα at redshift of 2.16±0.02. Alternative identifications such as [O II]λ3727 from $z \sim 0.02$ objects are unlikely, since the Hβ and [O III]5007 lines should then be visible in the spectra. Furthermore, the probability to observe a foreground galaxy is very small, since the differential volume element at $z \sim 0.02$ is 370 times smaller than that at redshift 2.16. One of the 15 emitters is an AGN. We also detect emission from several components of the central radio galaxy 1138–262, which we shall discuss in a companion paper (Kurk et al. *in preparation*).

Besides the 15 Lyα emitters, an additional 13 objects show (mostly faint) continuum emission, but none have detectable

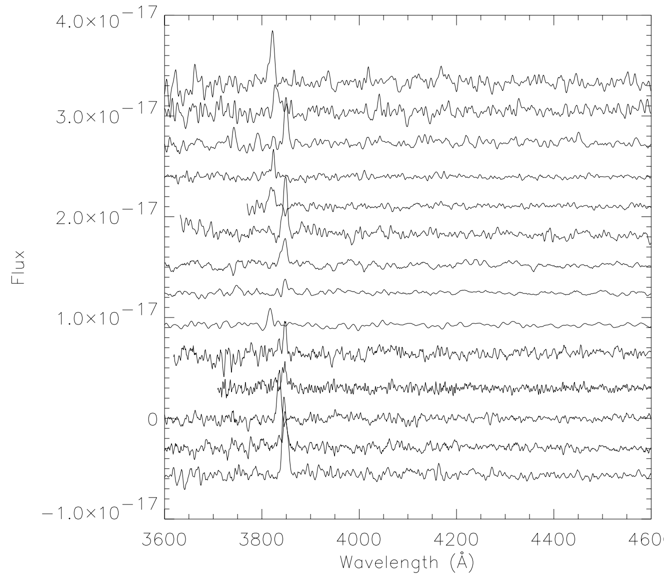

Fig. 1. The emission spectra of the 14 confirmed galaxies at redshift ~ 2.16. The flux is in ergs s^{-1} cm^{-2} A^{-1} and for clarity each spectrum is offset, relative to the ordinate, by multiples of 3×10^{-18} ergs s^{-1} cm^{-2} A^{-1}.

lines therefore their redshifts remain undetermined. Five of these 13 objects show a decrement in continuum around the wavelength which would correspond to a Lyman break at a redshift ~ 2, so they could also be high redshift galaxies. Alternatively this spectral shape could be attributed to evolved stellar populations in faint low redshift galaxies. Note that in general the objects observed do not have strong continuum emission, because of our selection criteria.

The success rate of our selection criteria is 70% for prime candidates (i.e. having an observed EQW > 195 Å), 40% for secondary candidates (having EQW > 130 Å), 19% for tertiary targets (EQW > 65 Å), and 17% for the rest. The undetected objects with large EQW all have low expected Lyα flux. Therefore the non–detections are probably due to a lack of signal to noise.

Spectra of the newly discovered galaxies are shown in Fig. 1 and that of the AGN in Fig. 2. In Table 1 we report the positions, the redshift calculated from the peak position of the Lyα emission, the total flux in ergs s^{-1} cm^{-2}, the rest frame EQW, the restframe deconvolved FWHM of the Lyα line in km s^{-1}, determined by fitting the emission with a Gaussian function. Most of the emission lines have, to a first approximation, symmetric shapes, although in some cases the lines show structures and in one object a velocity gradient. We will consider this aspect further in follow-up work. In Table 1 we also report the B-band magnitude determined from the broad band observations of Paper I.

The mean rest frame EQW for our sample of galaxies is 60 Å and the distribution is nearly uniform from 15 to 150 Å. There are several objects with EQW in excess of 100 Å. This is significantly different from what is obtained by Steidel et al. (2000) for a large sample of galaxies at redshift around 3: they find

Table 1. Emitter characteristics

Object	Position R.A. (2000)	Position Decl. (2000)	z	Flux 10^{-17} ergs s^{-1}cm^{-2}	EQW Å	FWHM km s^{-1}	B-mag
7	11 40 37.14	-26 32 08.2	2.143	5.6	63	510	25.4
387	11 40 55.31	-26 30 43.5	2.139	1.7	22	370	28.1
419	11 40 55.35	-26 30 36.9	2.141	2.1	≥136	940	28.0
724	11 40 57.50	-26 29 39.4	2.164	2.5	16	200	–
752	11 40 58.20	-26 29 34.1	2.170	5.5	122	540	–
759	11 40 46.89	-26 29 32.2	2.145	1.4	≥88	–	–
833	11 40 46.21	-26 29 03.2	2.155	4.0	≥60	480	–
856	11 40 49.41	-26 29 09.4	2.166	4.6	35	220	24.8
1189	11 40 57.11	-26 28 11.0	2.165	3.5	59	490	26.3
1240	11 40 59.16	-26 27 55.3	2.147	3.3	14	790	25.1
1405	11 40 44.45	-26 27 43.4	2.164	3.1	155	470	26.2
1518	11 40 36.88	-26 28 03.3	2.161	8.8	72	830	25.0
1557	11 40 59.07	-26 28 10.6	2.147	2.7	13	260	25.4
1612	11 40 55.28	-26 28 24.3	2.163	3.9	≥30	490	27.4
QSO1687	11 40 39.76	-26 28 45.3	2.183[a]	56	164	5800	24.8

[a] Uncertain due to the presence of absorption.

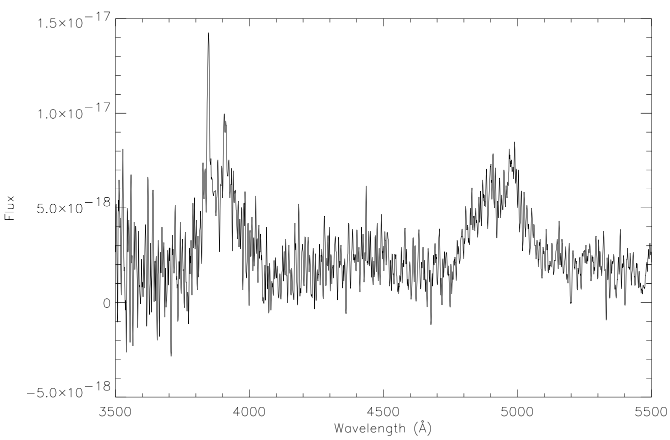

Fig. 2. The emission spectrum of QSO 1687, showing broad Lyα, Si IV and C IV emission lines. Lyα and C IV are partly absorbed.

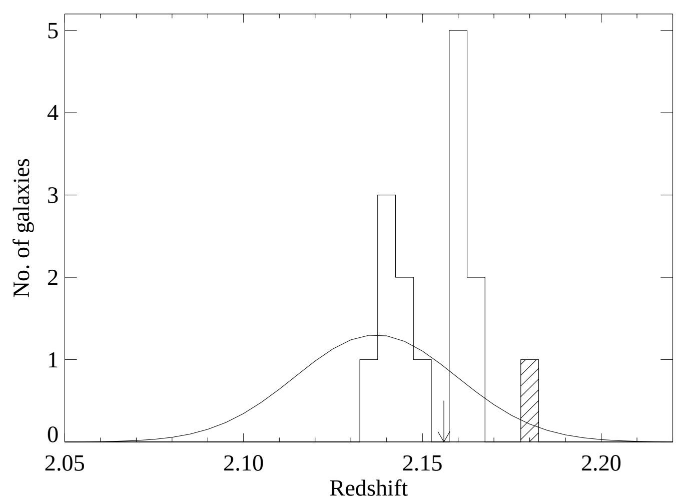

Fig. 3. The redshift distribution of the 15 emitters. The hatched bin contains the newly discovered QSO and the arrow denotes the redshift of the radio galaxy. The Gaussian curve represents the approximate response of the narrow band filter used to select the candidates.

no galaxies with EQW larger than 100 Å. While our results are most probably due to our observational strategy, that emphasizes large EQW objects, it is also possible that some of our targets contain an AGN component, since photoionization from hot stars is unlikely to produce rest frame EQW much higher than 100 Å (e.g. Charlot & Fall 1993).

The QSO shows Lyα, Si IV and C IV emission lines, and the Lyα has a FWHM of 5800 km s^{-1}. The Lyα and C IV lines have a double–peaked profile that is due to absorption by neutral gas. The fact that also C IV is absorbed indicates that the gas is metal enriched (e.g. Binette et al. 2000). The Lyα/C IV line ratio appears depressed compared to normal values for QSOs (Lyα/C IV ~ 2.5 from composite spectra of QSO BLRs, Osterbrock 1989). This could be caused by the presence of dust.

4. Discussion

In Fig. 3 we show the redshift distribution of the 15 newly discovered galaxies, together with a Gaussian curve representing the approximate normalized sensitivity of the narrow band filter, used at the beginning of the project to select the candidate emitters (Paper I). The velocities of the galaxies with confirmed redshifts are not distributed according to the selection function, but appear to be clustered around the redshift of the central radio source ($z = 2.156$).

It is instructive to compare the total comoving volume density of this structure of galaxies to that of the spike at redshift 3.09, found by Steidel et al. (2000), which consists of 24 galaxies and represents an overdensity of a factor ~ 6 compared to the field. Note that only 12 of these 24 galaxies have been subsequently also found using NB selection criteria similar to ours: the remaining ones have weak or absent Lyα emission or Lyα deficits. For a meaningful comparison, we adopt the same intrinsic luminosity cut as Steidel et al. (corresponding to their NB magnitude limit of NB ≤ 25, in AB magnitudes). This brings down the number of emitters we would have detected in our field to 4 (including the central radio galaxy). We then multiply this number by a factor two to compensate for the galaxies without Lyα emission. The comoving volume for our field size (8.2 Mpc^2) and redshift range ($2.139 \leq z \leq 2.170$) is 3830 Mpc^3, resulting in a volume density of 2.1 $\times 10^{-3}$ objects Mpc^{-3}. This is approximately equal to the density of the Steidel et al. spike, with 24 galaxies in a total comoving volume of 11040 Mpc^3, resulting in a density of 2.2 $\times 10^{-3}$ objects Mpc^{-3}.

The following obvious question is whether the overdensity of galaxies around 1138–262 is due to a structure that is, or will become, a gravitationally bound cluster. To investigate this matter further we discuss some additional properties of the data. The total velocity dispersion of the structure is 1200 $\pm$160 km s^{-1} (1000$\pm$140 km s^{-1} excluding the QSO), calculated as the standard deviation from the mean, i.e. assuming an underlying Gaussian velocity distribution. This would imply a mass larger than 5 (3.5) $\times$ $10^{14} M_{\odot}$, assuming a radius of 1.5 Mpc. However, the velocity distribution of the galaxies (Fig. 3) clearly differs from a Gaussian. The galaxies seem to cluster in two subgroups with seven members each, centered at median redshifts of 2.145± 0.002 and 2.164± 0.002, with the QSO as an outlier. Using the gapper sigma, suggested by Beers et al. (1990) as a better scale estimator for very small samples of objects, we obtain a velocity dispersion of 520 ± 140 km s^{-1} and 280 ± 70 km s^{-1} respectively. The implied total masses of each subgroup separately are considerably lower, $\sim 9\times10^{13} M_{\odot}$ and $\sim 3 \times 10^{13} M_{\odot}$. The detection of a larger number of galaxies is needed to establish the internal kinematics of these structures so that more definitive statements can be made about the virialization and mass distribution.

To further investigate possible spatial clustering of the galaxies we computed the angular two–point correlation function. The subgroups are too small to obtain any significant statistical results, but using the Landy-Szalay estimator (Landy & Szalay 1993) for the 15 galaxies and 1138–262, we detect a signal at distances of $\sim 25''$ due to the occurrence of 6 close pairs in our sample and at $\sim 150''$ with significance of 99.7% and 99.8% respectively. We also used the estimator introduced by Phillips (1985) to measure the correlation between the positions of observed objects and the position of a known object (in this case the radio galaxy), but the distribution of emitters around 1138–262 was not found to be significantly different from a random one. Although we find no significant spatial segregation between the two subgroups, this may be masked by (i) the small number of galaxies so far detected, (ii) bias introduced by constraints in the slit positions simultaneously accessible to the FORS MOS and (iii) our identification of all clumps within the 150–kpc sized Lyα halo surrounding 1138–262 as components of the central radio galaxy.

We note that the few high redshift clusters known show similar substructures and do not appear concentrated in the sky. Examples include the cluster around 3C234 (e.g. Dickinson 1997) at redshift ~ 1.1; the concentration of red objects at $z \sim 1.3$ found by Liu et al. (2000), and the structure found by Rosati et al. at redshift ~ 1.27, consisting of two collapsed systems (Rosati et al. 1999; Stanford et al. 1997). Similarly, Steidel et al. (2000) find that the distribution of the local density of galaxies for their z=3.09 spike, has 3 significant density peaks. Cluster substructures are not only frequently observed, but they are also consistent with the predictions of hierarchical models of galaxy and structure formation. As Governato et al. (1998) argue, such concentrations of galaxies at high redshift are probably the progenitors of local rich clusters. Given the small velocity separation, the velocity subgroups found in 1138–262 are likely to merge, evolving into the larger structures seen in the local Universe.

5. Conclusions

We have confirmed the existence of a substantial overdensity of galaxies within 1.5 Mpc of the high redshift radio galaxy 1138–262. We have found at least 15 galaxies at approximately the same distance as the radio source which seem to consist of two subgroups. The new results taken together with previous work show that 1138–262 at $z = 2.16$ has many ingredients that might be expected from a forming cluster, namely a substantial galaxy overdensity, a central galaxy resembling a forming massive central cluster galaxy and the presence of hot X-ray–emitting gas. These results also confirm that radio galaxies can be used to pinpoint regions of galaxies overdensity at high redshifts and to probe the formation of large–scale structures in the early universe.

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