The First VLT FORS1 spectra of Lyman-break candidates in the HDF-S and AXAF Deep Field

S.Cristiani1,2, I.Appenzeller3, S.Arnouts2,4, M.Nonino1,5, A. Aragón-Salamanca6, C.Benoist4, L.da Costa4, M.Dennefeld5, R.Rengelink4, A.Renzini4, T.Szeifert3, and S.White7

1 Space Telescope European Coordinating Facility, Karl-Schwarzschildstr. 2, D-85748 Garching, Germany
2 Dipartimento di Astronomia dell’Università di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy
3 Landessternwarte Königstuhl, D-69117 Heidelberg, Germany
4 European Southern Observatory, Karl-Schwarzschildstr. 2, D-85740 Garching, Germany
5 Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, 40131 Trieste, Italy
6 Institut d’Astrophysique de Paris - CNRS, 98bis Boulevard Arago, F-75014 Paris, France
7 School of Physics & Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, U.K.
8 Max-Planck Institut für Astrophysik, D-85740 Garching, Germany

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Abstract. We report on low-resolution multi-object spectroscopy of 30 faint targets \((R \approx 24 - 25)\) in the HDF-S and AXAF deep field obtained with the VLT Focal Reducer/low dispersion Spectrograph (FORS1). Eight high-redshift galaxies with \(2.75 < z < 4\) have been identified. The spectroscopic redshifts are in good agreement with the photometric ones with a dispersion \(\sigma_z = 0.07\) at \(z < 2\) and \(\sigma_z = 0.16\) at \(z > 2\). The inferred star formation rates of the individual objects are moderate, ranging from a few to a few tens \(M_\odot\) yr\(^{-1}\). Five out of the eight high-z objects do not show prominent emission lines. One object has a spectrum typical of an AGN. In the AXAF field two relatively close pairs of galaxies have been identified, with separations of 8.7 and 3.1 proper Mpc and mean redshifts of 3.11 and 3.93, respectively.

Key words: Techniques: spectroscopic; Galaxies: evolution, formation, distances and redshifts

1. Introduction

Observations of galaxies, now extending up to a redshift \(z \approx 6\) \citep{Hu1999}, are starting to provide quantitative information on basic properties - number densities, luminosities, colors, sizes, morphologies, star formation rates (SFR), chemical abundances, dynamics and clustering - over a large span of cosmic time. These data are beginning to sketch out a direct picture not only of the physical processes taking place in the assembly of the first galaxies, but also of the formation and evolution of large scale structure (LSS) from the primordial density fluctuations. Quantitative information is now available about the evolution of the neutral hydrogen and metal content of the universe since \(z \approx 4\), the galaxy luminosity function since \(z \approx 1\), the morphology of field and cluster galaxies since \(z \approx 0.8\). A recent dramatic addition to the general picture has been the discovery of a large population of actively star-forming galaxies at \(z \approx 3\) \citep{Steidel1996}. The “Lyman break” color-selection technique \citep{Steidel1992} has proved a reliable and highly efficient method to select galaxies in large numbers at \(z \approx 2.5\), providing the first opportunity for statistical studies of evolutionary processes in galaxies beyond \(z = 1\). Follow-up spectroscopy of the UV drop-out candidates on the Keck telescopes shows most to lie in the expected redshift range, \(2.5 \leq z < 3.5\), with successful redshift measurement for more than 70%. The Lyman-break galaxies have spectra resembling those of nearby starburst galaxies, are strongly clustered, with a co-moving correlation length similar to present-day galaxies. SEDAG96 inferred typical SFRs of \(1 - 6h^{-2}M_\odot\) yr\(^{-1}\) for their galaxies, assuming a critical density universe. Dust corrections based on the UV continuum slope and on near-IR spectroscopy of a few objects suggest values larger by a mean factor of about 7 \citep{Pettini1998}. From the width of saturated interstellar absorption lines, SEDAG96 inferred tentative 1D velocity dispersions in the range \(\sigma_1D = 180 - 320\) km s\(^{-1}\), but Pettini et al. (1998) measure in the IR significantly narrower line-widths \(\sigma_1D = 55 - 190\) km s\(^{-1}\) for the Balmer and [OIII] emission lines, albeit in a sample of only five objects.

A programme has been started with the ESO VLT to study systematically galaxies at \(z \approx 4\) with the aim to clarify the earliest phases of the processes leading to the formation of galaxies and LSS, reaching a redshift
domain where observations are more cosmologically discriminant (Arnouts et al., 1999) and taking advantage of a wide photometric coverage (in particular in the IR) to obtain mass estimates of the detected objects. We report here the results of pilot observations carried out during the commissioning and the science verification of the FORS1 instrument at the VLT-UT1.

2. The photometric databases and the selection of the candidates

Deep multicolor imaging of the HDF-S and AXAF deep field has been obtained from HST and from the ground. In particular WFPC2 data, consisting of deep images in the F300W, F450W, F606W and F814W filters, cover an area of 4.7 sq.arcmin reaching 10σ magnitude limits of 26.8, 27.7, 28.2 and 27.7 (in a 0.2 sq.arcsec area, Williams et al. 1999). UBVRJK data over an area of 25 sq.arcmin, including the WFPC2 field, have been obtained at the ESO 3.5m New Technology Telescope (NTT) as a part of the ESO Imaging Survey (EIS) program (da Costa et al., 1999). They reach 2σ limiting magnitudes of $U_{AB} \sim 27$, $B_{AB} \sim 26.5$, $V_{AB} \sim 26$, $R_{AB} \sim 26$, $I_{AB} \sim 25$, $J_{AB} \sim 25$, $H_{AB} \sim 24$ and $K_{AB} \sim 24$. The EIS survey observed also the AXAF1 field (Benoist et al., 2000). 25 sq.arcmin were covered in the EIS down to $U_{AB} \sim 27.0$, $B_{AB} \sim 27$, $V_{AB} \sim 26.5$, $R_{AB} \sim 26.5$ and $I_{AB} \sim 26$, $J_{AB} \sim 24.5$ and $K_{AB} \sim 23.5$. Photometric catalogs were derived from Lanzetta et al. (1999), da Costa et al. (1999) and Benoist et al. (2000). Lyman-break galaxy candidates were selected by the EIS team on the basis of two-color diagrams shortly after the EIS observations in order to provide targets for the FORS1 commissioning and Science Verification. A more refined selection has been carried out after the observations reported here on the basis of the photometric redshift technique described by Arnouts et al. (1999).

3. Spectroscopic Observations

The present data have been retrieved from the ESO Public Archive. Spectroscopic observations were carried out with the FORS1 instrument (Nicklas et al., 1997) in multiple object spectroscopy (MOS) mode on December 1998 by the FORS1 Commissioning Team and on January 1999 for the FORS1 Science Verification (see http://www.eso.org/science/utlis/) and Cristiani, 1999). In the FORS1 MOS mode 19 movable slit blade pairs can be placed in a FOV of 6.8 × 6.8 sq.arcmin. The actual useful field in the direction of the dispersion is somewhat less and depends on the length of the spectra/dispersion. In the present case the Grism H150 was used, providing a useful field of 3.5 × 6.8 sq.arcmin. One configuration of slits was observed in the HDF-S and two in the AXAF1. The journal of the observations is given in Table 1. When no suitable candidate was available for the allowed range of positions of a given slit, a random object in the field was chosen.

The MOS observations were reduced within the MIDAS package, using commands of the LONG and MOS contexts. For each object the available 2-D spectra were stacked and then an optimal extraction was carried out. Tables 2 and 3 give the photometric information and the redshift (when it has been possible to estimate it) for the objects observed in the HDF-S and AXAF deep field, respectively. In Column 1 the EIS identifier refers to Lyman-break candidates in the original EIS lists (for the AXAF field U- and B-dropouts are listed

### Table 1. Journal of the MOS Observations

| Field | $\alpha_{2000}$ | $\delta_{2000}$ | date | exp.time (s) |
|-------|-----------------|-----------------|------|-------------|
| HDF-S | 22:32:46         | -60:34:31       | 1998-Dec-15 | 1800 |
| HDF-S | 22:32:46         | -60:34:1        | 1998-Dec-16 | 3600 |
| HDF-S | 22:32:46         | -60:34:1        | 1998-Dec-18 | 1800 |
| HDF-S | 22:32:46         | -60:34:1        | 1998-Dec-19 | 1800 |
| HDF-S | 22:32:46         | -60:34:1        | 1998-Dec-19 | 1800 |
| HDF-S | 22:32:46         | -60:34:1        | 1998-Dec-20 | 1800 |
| AXAF1/A | 03:32:08     | -27:46:0         | 1999-Jan-16 | 2100 |
| AXAF1/A | 03:32:08     | -27:46:0         | 1999-Jan-21 | 2200 |
| AXAF1/A | 03:32:08     | -27:46:0         | 1999-Jan-22 | 2100 |
| AXAF1/B | 03:32:08     | -27:46:0         | 1999-Jan-18 | 2100 |
| AXAF1/B | 03:32:08     | -27:46:0         | 1999-Jan-19 | 2100 |
| AXAF1/B | 03:32:08     | -27:46:0         | 1999-Jan-19 | 1600 |
| AXAF1/B | 03:32:08     | -27:46:0         | 1999-Jan-22 | 2100 |

### Table 2. Spectroscopic Identifications in the HDF-S

| Ident. | $\alpha_{2000}$ | $\delta_{2000}$ | z  | $V_{AB}$ | $R_{AB}$ |
|--------|-----------------|-----------------|----|----------|----------|
| EIS 18 | 22:32:30:9       | -00:32:44       | -  | 25.18    | 24.92    |
| EIS 23 | 22:32:31:9       | -00:35:16       | -  | 25.25    | 24.81    |
| ANON15 | 22:32:34:3       | -00:35:52       | M  | 23.52    | 22.68    |
| ANON19 | 22:32:38:0       | -00:37:18       |    | 0.514    | -        |
| ANON18 | 22:32:38:7       | -00:37:02       |    | 0.410    | -        |
| EIS 33 | 22:32:40:0       | -00:36:21       |    | 24.36    | 24.04    |
| EIS 36 | 22:32:42:2       | -00:34:46       | M  | > 26.154 | 25.67    |
| ANON02 | 22:32:45:0       | -00:30:55       |    | 0.514    | -        |
| ANON17 | 22:32:45:9       | -00:36:40       |    | 0.852    | -        |
| EIS 43 | 22:32:47:0       | -00:31:46       |    | 24.52    | 24.40    |
| ANON03 | 22:32:48:5       | -00:31:16       |    | 0.516    | 24.31    |
| EIS 47 | 22:32:49:3       | -00:32:25       |    | 2.79     | 23.61†   |
| ANON01 | 22:32:49:4       | -00:30:41       |    | 0.776    | -        |
| EIS 52 | 22:32:53:1       | -00:32:06       |    | 25.10    | 24.49    |
| EIS 54 | 22:32:53:5       | -00:33:12       |    | 25.08    | 24.86    |
| EIS 53 | 22:32:53:5       | -00:35:24       |    | 3.521    | 24.92    |
| ANON09 | 22:32:53:7       | -00:33:37       |    | 0.566    | 22.52    |
| EIS 58 | 22:32:54:7       | -00:34:31       |    | 24.61    | 24.22    |
| EIS 60 | 22:32:55:4       | -00:33:55       |    | 26.32    | 25.30    |

† complex morphology: photometry from Lanzetta et al. 1999.
Fig. 1. Spectra of 8 high-redshift galaxies observed in the HDF-S and AXAF deep field. The ordinate gives the relative flux density per Angstrom.

with the “EIS U” and “EIS B” prefix, respectively). Random-chosen objects are listed with the “ANON” prefix followed by the number of the slit in which they were placed. The spectra of 8 galaxies with redshifts between 2.8 and 4.0 are shown in Fig. 1. These and more spectra are available in digital form at the URL [http://www.eso.org/science/ut1sv/MOSDR.html](http://www.eso.org/science/ut1sv/MOSDR.html). In some cases (HDF-S: EIS 23, EIS 33, EIS 52; AXAF: EIS U19, EIS B12) it was not possible to determine a redshift due to the lack of significant spectral features rather
than to an insufficient S/N of the spectrum. The photometric data of Columns 5 and 6 have been taken from the EIS database in its most recent version (Arnouts, private communication). Five HDF-S ANON targets lie outside the EIS images and no photometry is provided for them.

4. Discussion

At present, the spectroscopy of candidate Lyman-break galaxies has been restricted to an area of 13.5 sq.arcmin in the HDF-S in which $UBVRIJK$ imaging is available and 25 sq.arcmin in the AXAF deep field (22 sq.arcmin covered in $UBVRIJK$ and 3 sq.arcmin in $UBVRI$ only). After the FORS1 spectroscopic observations, which were based on a preliminary list of Lyman-break candidates produced shortly after the EIS imaging observations, we carried out a more refined selection of galaxies with $z > 2.75$ on the basis of a photometric redshift code (described in Arnouts et al. 1999).

In this paper $SFR$ has been restricted to an area of 13.5 sq.arcmin in the HDF-S in which $UBVRIJK$ imaging is available and 25 sq.arcmin in the AXAF deep field (22 sq.arcmin covered in $UBVRIJK$ and 3 sq.arcmin in $UBVRI$ only). After the FORS1 spectroscopic observations, which were based on a preliminary list of Lyman-break candidates produced shortly after the EIS imaging observations, we carried out a more refined selection of galaxies with $z > 2.75$ on the basis of a photometric redshift code (described in Arnouts et al. 1999).

In the HDF-S 25 candidates have been found down to a limiting mag of 25. Of the total 61 candidates 10 turned out to have been observed during Commissioning and Science Verification: 8 of them have been confirmed to be at high redshift, 2 resulted in inconclusive spectra. Fig. 2 shows the comparison between photometric and spectroscopic redshifts for the 8 galaxies with $z > 2.75$ observed so far in the HDF-S and AXAF field. The resulting dispersion is $\sigma_z(z > 2.75) = 0.16$.

At lower redshift, including some preliminary results in surveys based on the “Lyman-break” technique, the inferred star formation rates are moderate, ranging from a Salpeter IMF ($0.1 M_\odot < M < 125 M_\odot$) with constant $SFR$, a galaxy with $SFR = 1 M_\odot$ yr$^{-1}$ produces $L(150 \text{ nm }) = 10^{40.15} \text{ erg s}^{-1} \text{ Å}^{-1}$ (Madau et al., 1996).

Table 3. Spectroscopic Identifications in the AXAF Deep Field

| Identifier | $\alpha_{2000}$ | $\delta_{2000}$ | $z$ | $V_{AB}$ | $R_{AB}$ |
|------------|----------------|----------------|-----|---------|---------|
| ANON14     | 03:32:03.5     | -27:47:31      | 1.157 | 24.02 | 24.32 |
| EIS U28    | 03:32:03.6     | -27:43:40      | 3.132 | 24.79 | 24.87 |
| EIS U12    | 03:32:04.4     | -27:46:03      | 3.083 | 24.77 | 24.68 |
| EIS U21    | 03:32:05.0     | -27:44:32      | 3.462 | 23.65 | 23.74 |
| EIS B07    | 03:32:05.1     | -27:46:12      | 3.912 | 25.15 | 24.67 |
| EIS U01    | 03:32:05.8     | -27:48:16      | star? | 23.64 | 22.98 |
| EIS B02    | 03:32:06.6     | -27:47:47      | 3.939 | 25.47 | 24.68 |
| EIS U14    | 03:32:09.1     | -27:45:35      | -     | 25.37 | 24.95 |
| EIS B06    | 03:32:09.2     | -27:46:53      | Mstar | 26.39 | 25.02 |
| EIS U19    | 03:32:09.6     | -27:45:14      | -     | 25.48 | 25.02 |
| EIS B12    | 03:32:10.1     | -27:44:10      | -     | 25.14 | 24.50 |

Table 4. Properties of the Galaxies with $z > 2.5$ in the HDF-S and AXAF fields

| Identifier | SFR Uncorr. $M_\odot$/yr | $E_{BV}$ mag | SFR Corr. $M_\odot$/yr | Age Gyr | Mass log($M_\odot$) |
|------------|--------------------------|--------------|------------------------|---------|-------------------|
| HDF-EIS43  | 8                        | 0.0          | 8                      | 0.7     | 10.6              |
| HDF-EIS47  | 15                       | 0.1          | 38                     | 0.1     | 11.2              |
| HDF-EIS53  | 12                       | 0.1          | 19                     | 0.1     | 10.8              |
| AX-EISU28  | 6                        | 0.2          | 13                     | 1.4     | 10.9              |
| AX-EISU12  | 6                        | 0.0          | 6                      | 0.1     | 10.0              |
| AX-EISU21  | AGN                      |              |                        |         |                   |
| AX-EISB07  | 12                       | 0.0          | 12                     | 1.0     | 10.5              |
| AX-EISB02  | 12                       | 0.0          | 12                     | 0.7     | 10.5              |

Fig. 2. Comparison of photometric and spectroscopic redshifts in the HDF-S and AXAF deep field.
objects in the present sample any statistical conclusion is obviously impossible, but it appears natural to link the occurrence of the two pairs to the redshift “spikes” observed by Steidel et al. (1998) at $z \approx 3$. Future observations of the remaining high-z galaxy candidates and the extension of the surveyed area (see http://www.eso.org/science/eis/) will make it possible to address also this issue on a more quantitative basis.

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