GOODS' Look at Galaxies in the Young Universe

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The Great Observatories Origin Deep Survey is using the most advanced observing facilities, ESO/VLT, HST, Spitzer, Chandra, XMM/Newton, etc. to discover infant galaxies at epochs when the Universe was only 900 million years old. The FORS2 spectroscopic survey has confirmed 33 galaxies in the redshift interval $5 < z < 6.2$, producing one of the largest spectroscopic samples in that redshift range to date.

The quest for primordial galactic structure

One of the major goals of contemporary cosmology is to understand the processes leading to the formation of galaxies. According to the present standard model the growth of structure, from the first tiny fluctuations of matter (about one part over 10^5 at the time of recombination, as recorded by CMB experiments) to galaxies and clusters of galaxies, advanced through hierarchical mergers of dark matter concentrations. Eventually the gravity of the largest aggregates grew enough to pull in and concentrate the gas needed to build infant galaxies. The first generations of stars are thought to have produced the ultraviolet photons needed to reionise the Universe ending the Dark Ages that had followed the recombination.

Astronomers are closing the gap between the CMB experiments, i.e. the epoch recombination 380 000 years after the Big-Bang, and the observations of primordial galaxies, thanks to the development of more and more powerful instruments. Taking advantage of the imaging capabilities of the Advanced Camera for Surveys (ACS) onboard the Hubble Space Telescope and the spectroscopic power of the FORS2 instrument at the ESO/VLT our team has been able to identify a substantial population of galaxies at redshifts up to 6.2, when the Universe was only 900 million years old. The programme has been carried out in the framework of the Great Observatories Origins Deep Survey (GOODS), which unites extremely deep observations from NASA's Great Observatories, the Spitzer Space Telescope, Hubble, and Chandra, ESA's XMM-Newton, and from the most powerful ground-based facilities, ESO/VLT, Keck, etc. (the GOODS project has already been described in a previous article (The Messenger 118, 45)).

The GOODS HST Treasury Program uses the ACS to image the HDF-N and CDF-S fields through four broad, non overlapping filters: F435W (*B*), F606W (*V*), F775W (*i*) and F850LP (*z*). The exposure time is 3, 2.5, 2.5, and 5 orbits per filter, respectively, reaching extended-source sensitivities within 0.5–0.8 mags of the WFPC2 HDF observations. GOODS is a deep survey, not a wide one, but it is much larger than most previous, deep HST/WFPC2 surveys, covering 320 square arcmin, 32 times the combined solid angles of the HDF-N and S, and four times larger than their combined flanking fields. The *z*-band observations image the optical restframe light from galaxies out to $z = 1.2$, with angular resolution superior to that from WFPC2. The ACS *BViz* imaging makes possible a systematic survey of Lyman break galaxies at $4 < z < 6.5$, reaching back close to the epoch of reionisation.

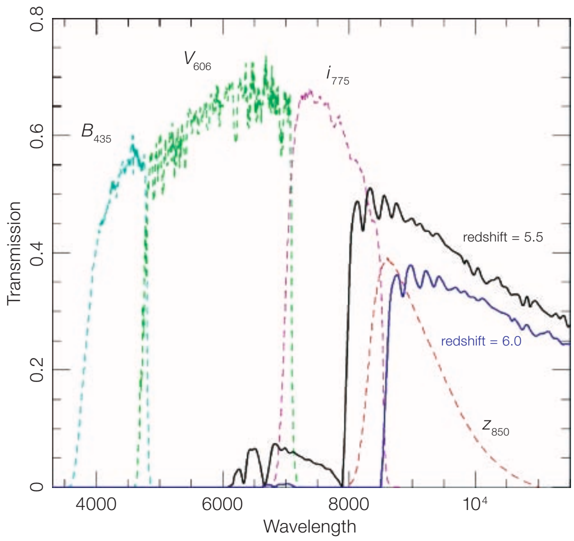
How are the primordial galaxy candidates selected?

High-redshift objects can be identified by sharp breaks in their spectra due to strong absorption of the UV photons by intervening hydrogen gas. Multi-colour imaging identifies these sources as they "disappear" in images taken through filters sensitive to light with wavelengths shorter than that of the break (also known as "dropout" or "Lyman break" technique). An example is shown in Figure 1, where in the upper panel two model spectra of starburst galaxies are superimposed on the four ACS filter transmissions. In this illustrative example the fluxes of the galaxies drop in the *B*-, and *V*- (and also in the *i*-band for the redshift 6 galaxy) due to the high-redshift nature of the sources. In the bottom panel, the direct images of Lyman break galaxies at redshifts 5.5 and 6.0 are shown: the source at redshift 6 "disappears" in the *B*-, *V*- and *i*-filters. This Lyman break technique for identifying distant star-forming galaxies has been in use for over a decade and was championed by Steidel and collaborators to find $z = 3$ and 4 galaxies (Steidel et al. 1999).

At redshift $z < 5.5$ the technique involves three filters: one below the Lyman limit ($\lambda_{rest} = 912$ Å), one in the Lyman forest region and a third longward of the Lyman-α line ($\lambda_{rest} = 1216$ Å). For example, in this way Giavalisco et al. 2004a selected samples of star-forming galaxies at redshifts between 3.5 and ~ 5.5 in the GOODS fields. At redshift > 5.5, only two filters can be (effectively) used, since the integrated optical depth of the Lyman-α forest is >> 1 and the break in the Spectral Energy Distribution (SED) is located between the *i*- and *z*-filters. The key issue is to work at a sufficiently high signal-to-noise ratio that the *i*-band dropouts can be safely identified through detection in a single redder band (i.e. the *z*-band). This is guaranteed by the exquisite images obtained with the ACS onboard HST.

The expected colour (*i–z)* of a star-forming galaxy at redshift > 5.5 increases with increasing redshift because the break at the Lyα wavelength (1216 Å) shifts out of the *i*-band (see Figure 1). In this way adopting a simple colour cut of $(i–z) > 1.3$

it is possible to select $z > 5.5$ galaxies. The old stellar populations of elliptical galaxies at redshift around 1–2 have also very red colours (Extremely Red Objects, or EROs) and may contaminate the samples of colour-selected high-redshift galaxies. This is due to the fact that the 4 000 Å break of an evolved stellar population at redshift around 1–2 moves beyond the *i*-filter producing redder colours. Also Galactic cool dwarf stars can contaminate the sample, in particular at the bright end of the magnitude distribution. Recent results from the FORS2 spectroscopic campaign in the same field at lower redshift show that the mean $(i–z)$ colour for ~ 50 early-type galaxies at redshift 1–1.3 is 0.9 ± 0.2, with a maximum of 1.25, consistent with the colour predicted for a typical (L*) non-evolving elliptical galaxy in that redshift interval (Vanzella et al. 2005). The availability of a wide multi-band coverage in the GOODS field, in particular the near- and mid-infrared observations performed with the VLT/ISAAC and the Spitzer/IRAC facilities (from 1 to 8 microns) helps to disentangle between high-redshift star-forming galaxies and lower-redshift sources on the basis of their spectral energy distribution.



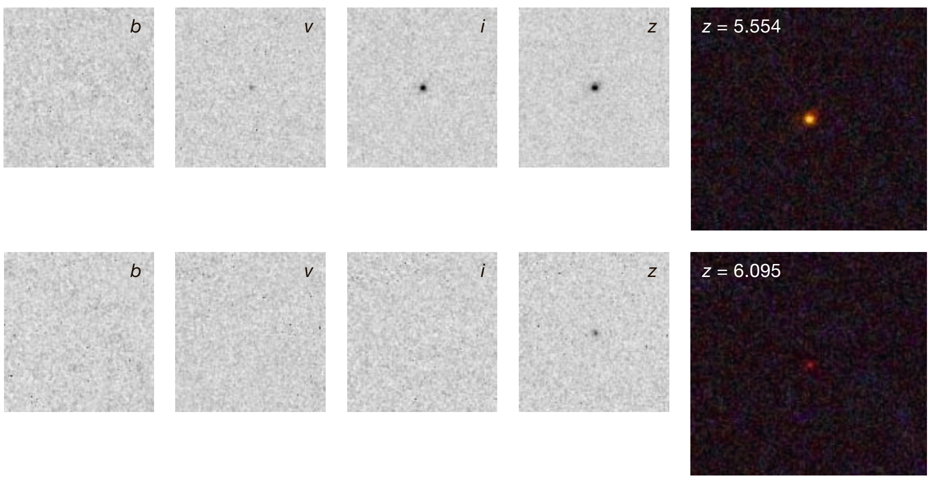


Figure 1: An example of the Lyman break technique. In the upper panel two model spectra of starburst galaxies calculated at redshift 5.5 and 6.0 are superimposed on the four ACS filter transmissions. The bottom panel shows the direct images of two observed Lyman break galaxies at redshift 5.554 and 6.095, respectively. Note how the source at redshift 6 "disappears" in the filters *B*, *V* and *i*.

Spectroscopic confirmation and redshift measurement

Although the colour selection is very accurate with the exquisite data described above, it is still important to get a spectrum of the candidates to measure their redshift beyond any reasonable doubt and obtain information about their physical and chemical properties. Reliable redshifts provide the time coordinate needed to delineate the evolution of galaxy masses, morphologies, clustering, and star formation. This is precisely the goal of the spectroscopic follow-up carried out by our team with FORS2 at the ESO/VLT. *I*-band dropouts (and also *B*- and *V*- band dropouts) have been observed in multiple spectroscopic masks and co-added in order to improve the S/N ratio. The total exposure time ranges from 10 000 to ~ 80 000 seconds.

Figure 2 shows the two-dimensional FORS2 spectra (from 6 600 Å to 10 000 Å) of 33 galaxies at redshift $z > 5$ (25 of them are *i*-band dropout sources at $z > 5.3$).

The redshift determinations, shown at the left-hand side of each sub-panel in the figure, have different quality (7 are certain, 13 are possible and 13 tentative) and the sources will be described in detail in a forthcoming paper (Vanzella et al., in preparation).

At present, the success rate of the colour selection of these very high-redshift galaxies is 96 %. As expected and shown in Figure 3, the majority of the galaxies at redshift > 5.4 are redder than $(i–z) = 1.3$. There are five sources with a $(i–z)$ colour bluer than 1.3. These are galaxies with redshift between 5.4 and 5.6 (the two star symbols in Figure 3 represent two sources in the redshift interval 5.4–5.5) at the limit of redshift selection using a simple colour cut. Part of them have been selected as *V*-dropout sources. The application of the photometric redshifts technique, exploiting all the photometric information available in the GOODS field, will improve the selection of high-*z* galaxies.

Properties of the Lyman-break galaxies

The spectra are in general very blue, indicating the presence of young stellar populations with ages of the order of 10^7–10^8 years, consistently with the UV colour selection adopted. Figure 4 shows the composite rest-frame UV spectrum constructed stacking 25 emission-line spectra in the redshift range $5.1 < z < 6.2$ ($<z> = 5.72 \pm 0.26$). The Lyα emission line, the break and the flatness of the continuum redward of the Lyα are clearly visible. The rest frame equivalent width of the

Lyα line turns out to be ~ 30 Å, comparable with the value measured for emission-line LBGs at redshift 3 (Shapley et al. 2003). The shape of the UV continuum is suppressed shortward of the Lyα by a decrement due to intergalactic H I absorption. In one galaxy the N IV]-1485 Å emission line is also detected, suggesting that we are seeing H II regions characterised by very hot ionising stars (Fosbury et al. 2003). It will be interesting to compare the properties of our sample based on the Lyman-break selection with the survey by Hu et al. 2004, which selects Lyman-α emitters on the basis of narrow-band imaging. Thanks to the large number of spectroscopically confirmed galaxies and from the ultraviolet continuum, it is possible to estimate (after correction for dust extinction) the global star-formation rate of the Universe at $z \sim 6$ (e.g. Giavalisco et al. 2004, Dickinson et al. 2004) and their contribution to the reionisation of the Universe (e.g. Panagia et al. 2005). But GOODS is much more. From the VLT/ISAAC and Spitzer/IRAC observations covering the electromagnetic spectrum from 1.2 to 8 microns, in combination with the current high-redshift sample, it will be possible for the first time to conduct a systematic study of the stellar-mass content of galaxies at $z \sim 6$ and explore even earlier formation times (e.g. Eyles et al. 2005 for two *i*-dropout galaxies).

The present sample will also allow us to study the presence of large-scale structure and the clustering properties of galaxies at such primordial epochs (e.g. Lee et al. 2005) giving an indication on the typical masses of the dark matter halos in which they reside. In these ways GOODS is providing stringent tests of scenarios of galaxy formation.

Figure 2: A sample of two-dimensional spectra of galaxies at $z > 5$ discovered during the ESO/FORS2 spectroscopic survey in the GOODS-S field. The position of the Lyα line is marked with a circle and where Lyα is not present the continuum break is underlined with a segment. The quality of the redshift determination depends on the reliability of the spectral features detected (i.e. on the S/N ratio). The source at $z = 5.400$(*) shows a blue continuum blueward of the Lyα line, because this spectrum is a combination of two close sources in the slit, an *i*-band dropout candidate and a lower-redshift object.

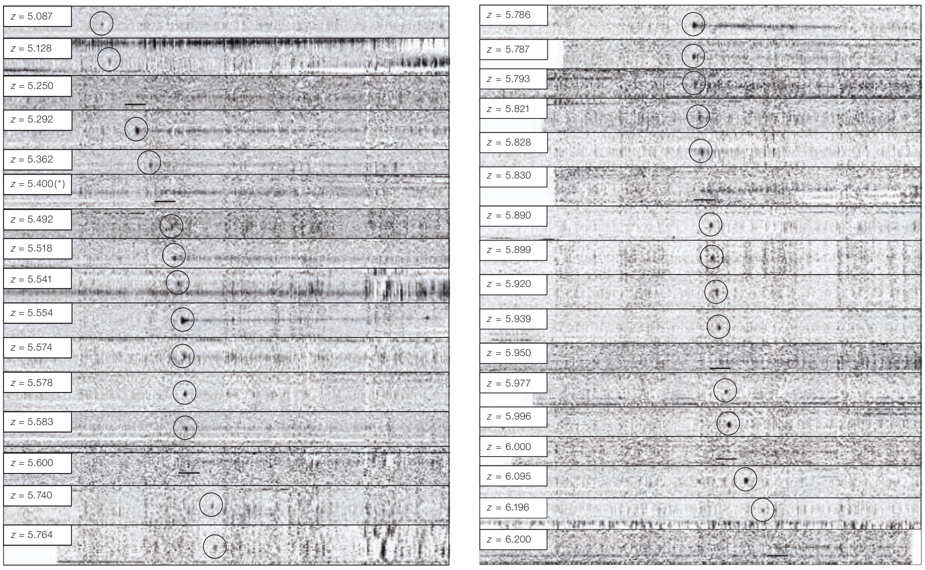


Figure 3: Colour-magnitude diagram for the selection of *i*-band dropout galaxies. The colour cut $(i–z) = 1.3$ (dashed line) outlines the region of the selection. The black dots are all sources down to $z = 27.5$. The open circles represent objects with redshift > 5.4 and the arrows indicate the 1σ lower limit in the $(i–z)$ colour. The size of the symbols scales with the spectroscopic redshift value. Star symbols are sources with $5.4 < z < 5.5$. Sources with an uncertain spectroscopic redshift are identified with a square.

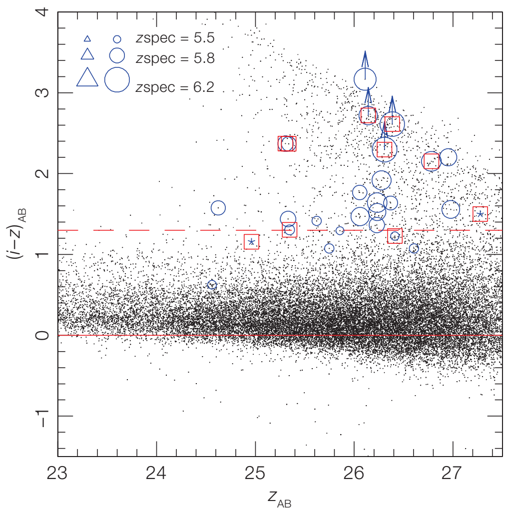
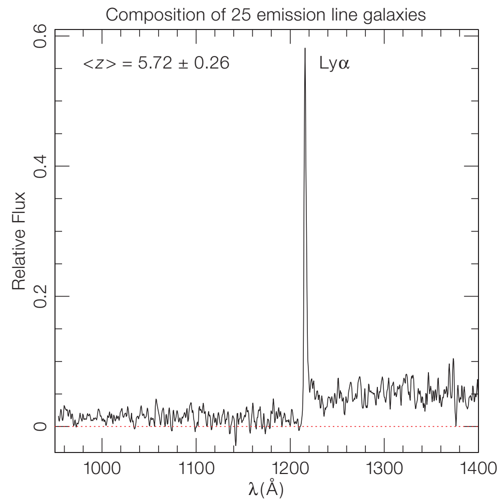


Figure 4: A composite spectrum of 25 emission-line Lyman break galaxies in the redshift interval $5.2 < z < 6.2$ (the mean of the redshift distribution is $<z> = 5.72 \pm 0.26$). The Lyα line and the break in the continuum blueward of the emission are apparent.



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