The VLT VIMOS Lyman-break Galaxy Redshift Survey — First Results

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We have completed the largest spectroscopic survey of Lyman-break galaxies (LBGs) at $z \approx 3$, using the uniquely wide field of the VLT VIMOS multi-object spectrograph. The survey now contains about 2100 galaxy redshifts over the range $2 < z < 3.5$ and is being used to investigate gas outflows from galaxies and large-scale structures at $z \approx 3$. These results are having an immediate impact on theories of galaxy formation and producing new tests of the standard cosmological model. In particular, we find: further evidence from their clustering that LBGs may be the progenitors of spiral galaxies; new evidence for gas outflows from star-forming galaxies as required by theoretical galaxy formation models; and new evidence for gravitational infall of galaxies into clusters at a rate that is consistent with the standard cosmology.

The Lyman-break technique uses the redshifting of the Lyman-α forest and Lyman-break into the *U*-band to detect $2.5 < z < 3.5$ galaxies. Use of this technique originated in the mid-1980s when it was applied to find $z > 3$ QSOs (Shanks et al., 1983). Further development of the method for selecting $z > 3$ galaxies came in the subsequent years as deeper optical imagery became available (Guhathakurta et al.,1990; Steidel & Hamilton, 1993). However, the first significant galaxy redshift surveys at $z \approx 3$ did not come until the mid-1990s when surveying of these objects was begun with the Keck LRIS spectrograph (e.g., Steidel et al., 1996) and secure galaxy redshifts could be determined.

Faint blue galaxies at high redshift

The early scientific results from these surveys were intriguing. Prior to the confirmation of these faint blue objects as $z > 2$ galaxies, there was a perception that star formation should be suppressed at $z > 1$ in line with predictions from cold dark matter models. This was supported by the sparsity of observations of $z > 1$ galaxies at the time, which was in fact a selection effect, i.e. the redshift desert due to the [O II] line leaving the optical bands had conspired to produce false agreement with the model predictions.

Metcalfe et al. (1991, 1996) suggested that these faint blue galaxies, which dominate blue galaxy counts, may well be high redshift galaxies with their ultraviolet light from star formation redshifted into the visible bands. Only with the arrival of larger telescopes (such as Keck and the Very Large Telescope, VLT) armed with sensitive slit spectrographs did it become possible to cross the desert and pick up the UV light and, crucially, the Lyman-α emission line as it entered the optical bands at $z > 2$. At this point, it was found that a large fraction of faint blue galaxies were faint because they were at high redshifts and not intrinsically subluminous lower redshift galaxies. These galaxies, selected via the Lyman-break technique, and therefore termed Lyman-break galaxies, were more clustered than expected, leading to suggestions that they were the progenitors of early-type galaxies. They were predicted to have a morphology that was chaotic, appropriate for proto-galaxies, however in more recent years the results show that in fact many may have rotation curves rather like spiral galaxies.

Starburst outflows from forming galaxies?

Interestingly, the Keck LBG redshift data showed evidence for significant velocity offsets (≈ 600 km/s) between Lyman-α (Lyα) emission and absorption lines originating in the interstellar medium (ISM) in the LBG spectra, whilst at the same time the Lyα emission appeared to be asymmetric. These observations led to the development of the shell model for LBG structure in which a central star-forming region is surrounded by a shell of outflowing gas powered by the star formation in the central region. In this way the Lyα emission is scattered and absorbed by outflowing material, leading to the asymmetry and the velocity offsets between emission and absorption lines.

Further evidence for star formation feedback was also found in results showing LBGs close to the line of sight of $z > 3$ QSOs, which appeared to be associated with a deficiency of neutral hydrogen in the Lyman-α forest. The suggestion was that this was caused by the LBG outflows heating the surrounding gas (Adelberger et al., 2003). However, subsequent observations then contradicted this conclusion with no such deficit being observed in the larger, albeit somewhat lower redshift, sample presented by Adelberger et al. (2005).

VLT VIMOS LBG Redshift Survey

A key advantage of the VLT VIMOS is its large field of view. In one pointing, it covers a field of view of approximately 17 × 18 arcminutes, considerably larger than the field of view of approximately 6 × 8 arcminutes of the LRIS on Keck. Taking advantage of this, the VLT LBG survey has observed a total of 18 VIMOS fields, covering a total area of around 2.6 square degrees (Bielby et al., 2011; Crighton et al., 2011). A subset of the LBG fields is shown in Figure 1, where spectroscopically confirmed LBGs, identified using VIMOS, are denoted by blue circles and $z \approx 3$ QSOs from a range of sources are shown by red stars. In total the survey comprises around 2100 spectroscopically confirmed $z > 2$ galaxies, and in Figure 2 we show a number of example spectra of R ≈ 24.5 mag LBGs taken using VLT VIMOS.

The spectroscopic observations that form the survey have relied on high quality deep imaging, which for the most part has been obtained using the MOSAIC imagers at the NOAO KPNO and CTIO facilities. These large MOSAIC imagers have provided the survey with 35 × 35 minute coverage of the fields (a large enough area to allow four VIMOS pointings per imaging dataset — the lower panels of Figure 1), each of these being centred on a bright $z \approx 3$ QSO.

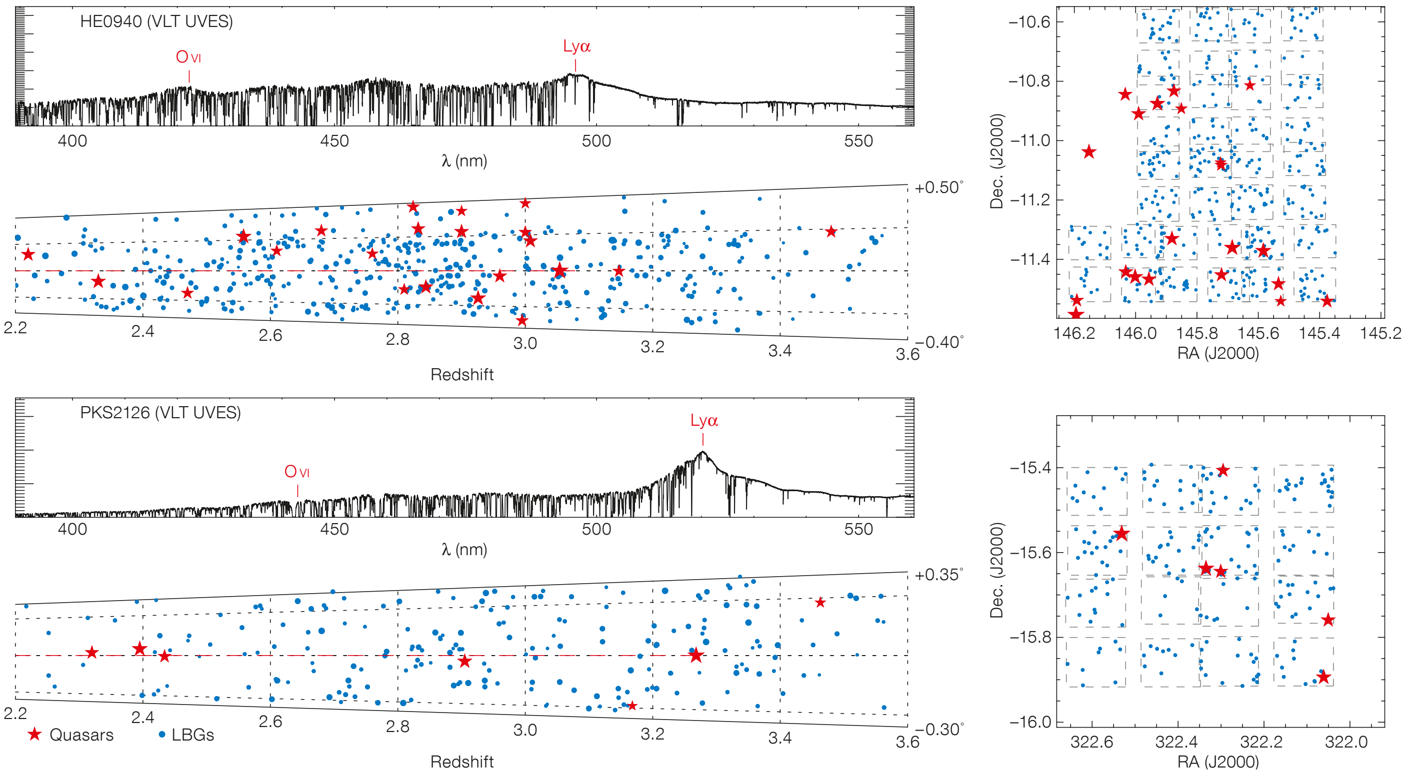

Figure 1. Left: The distribution in redshift and declination of LBGs and QSOs in two of our nine survey fields. LBGs spectroscopically confirmed using VIMOS are shown by blue circles; QSOs spectroscopically observed using AAT AAOmega or VLT UVES are shown by filled red stars. The UVES spectra of the central QSO is pictured above each cone and these show the Lyman-α absorption forest extending below the QSO Lyman-α emission line. Other metal lines can be seen at longer wavelengths. These hydrogen and metal absorption lines allow us to probe the intergalactic gas in the vicinity of the star-forming LBGs. Right: The same two fields, now shown projected onto the sky. The dashed grey boxes show the VIMOS observation areas for the VLT LBG Survey. The upper field contains nine VIMOS pointings and the lower field contains four VIMOS pointings.

More recently, a larger area capability has been added using the MegaCAM instrument at CFHT, which provides a field of view for the deep imaging of 1 × 1 degrees (allowing nine VIMOS pointings for each set of imaging data — the upper panels of Figure 1). Using these combinations of data, the VLT LBG survey has broken new ground in the observation of large-scale structure of galaxies at $z \approx 3$.

In order to probe the intergalactic medium, the survey also requires spectroscopic observations of $z \approx 3$ QSOs, which trace out the hydrogen content of the Universe along the line of sight. Where available we have made use of high resolution/high signal-to-noise spectra using VLT UVES and available through the ESO public archive. These only provide 1–2 QSO sightlines per field and we have added to this with a QSO survey within the VLT LBG fields using the AAOmega instrument on the Australian Astronomical Telescope (AAT). The AAOmega spectrograph easily encompasses our fields with its 2-degree field of view and in total has provided data on about 100 $z \approx 3$ QSOs in the VLT LBG fields, adding considerably to the available sightlines.
For the brighter QSOs identified via these

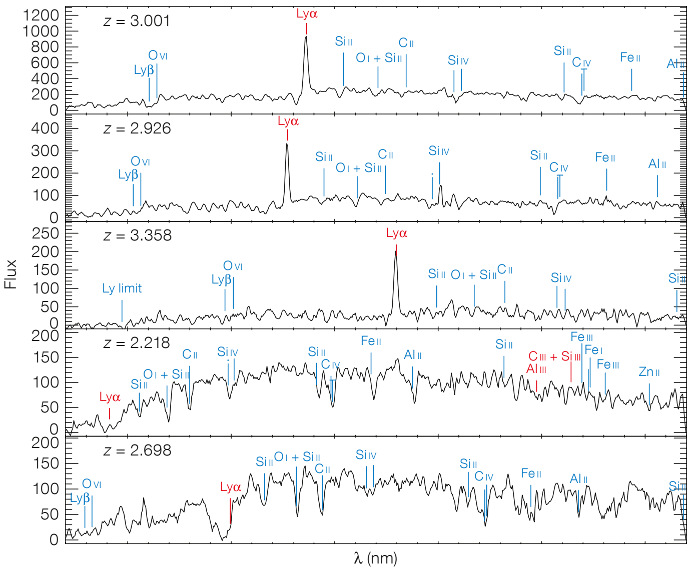

Figure 2. LBG spectra taken with VIMOS as part of the VLT LBG survey. The LBGs have $R \approx 24.5$ mag and the typical VIMOS on-sky exposure time was 3 hrs, using the low resolution LR-blue grism. Most of our redshifts are obtained via the Lyman-α line either in emission or absorption, but many other interstellar absorption lines can also be seen.

lower resolution AAOmega observations, we then measure high resolution/high signal-to-noise spectra using the VLT's X-shooter to provide improved maps of the Lyα-forest and metal-line distribution in many additional sightlines in our fields.

Galaxy clustering evolution

We first looked at the clustering of the LBGs. The first aim is to measure the amplitude of clustering which can discriminate between models for the evolution of the galaxies. We measured the clustering amplitude and then compared it to a simple model that assumes that the LBG is a progenitor of a spiral. For biased populations that assumption leads to a simple prediction for the clustering when dark matter haloes can grow by merging, but the galaxies are not allowed to merge. We find that there is then agreement with the clustering of high luminosity spirals or low luminosity early-types at $z = 0$ (see Figure 3). This is consistent with previous results where the luminosity function of LBGs at $z \approx 3$ was found to be consistent with an evolved luminosity function for local spiral galaxies.

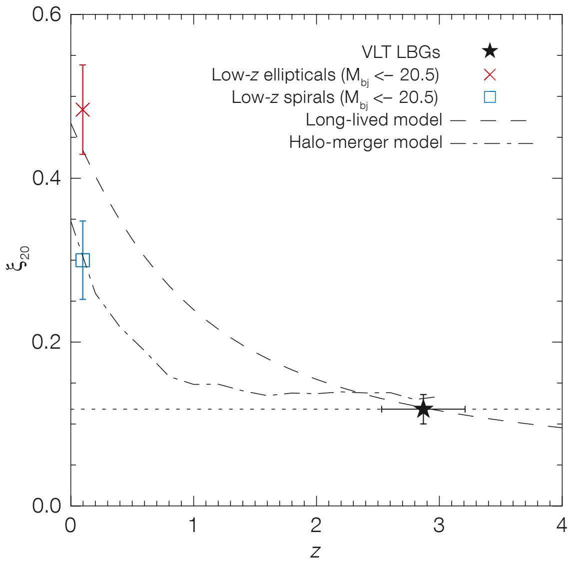

Figure 3. Predicted evolution of LBG clustering to the present day from Bielby et al. (2011). ξ_{20} measures galaxy clustering averaged out to 20 h^{-1} Mpc scales. A model where the LBGs are long-lived is consistent with them evolving into early-type galaxies by the present day, while a halo merger model could see them evolving into present-day spiral galaxies.

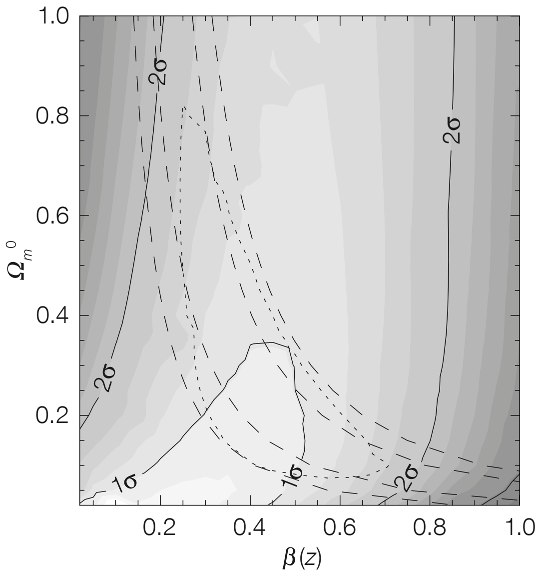

Figure 4. Fitting of the present-day value of Ω_m ($z = 0$) and the $z = 3$ infall parameter (β) based on the clustering measurements of the VLT LBG survey sample. The greyscale contours come from LBG redshift-distortions and the dashed contours come from the overall amplitude of the LBG clustering. These techniques provide reasonably independent constraints on the two unknowns, Ω_m ($z = 0$) and β ($z = 3$), allowing for their joint solution (dotted contours). The data suggest Ω_m ($z = 0$) ≈ 0.3 and $\beta \approx 0.45$, both consistent with the predictions of the standard cosmological model.

LBG z-space distortions and cosmology

The LBG clustering was further investigated for z-space distortions. The observed LBG clustering is measured in redshift-space, where Hubble's Law is naively used to convert redshifts into distances in the z direction. By comparing the clustering in the angular direction and the redshift direction the effect of velocity errors and peculiar velocities can be found. At small galaxy separations root mean square peculiar velocities and errors dominate, producing "fingers-of-god" elongated clusters in the redshift direction. At larger separations, dynamical infall dominates and flattens the clustering in the line of sight. Generally we have found LBG velocity dispersions of about 500 km/s, higher than found previously from the Keck survey, both in our re-analysis of that survey and in the VLT survey data. As well as having intrinsic interest, we shall see that the LBG velocity dispersion is a crucial parameter in interpreting the galaxy–gas relationship below. At larger scales we can estimate the parameter β that measures the rate of dynamical infall of galaxies into clusters. For standard gravity, $\beta = \Omega_m^{0.6}/b$ where Ω_m is the cosmological density parameter and b is the bias, or how much more the galaxies are clustered than the underlying mass. At these redshifts the cosmological density parameter should effectively be around one, whatever its value at $z = 0$. This makes it easy to determine the bias and we have found values which are pretty consistent with the standard Lambda Cold Dark Matter (ΛCDM) cosmological model, i.e. the amplitude of mass clustering implied by the LBG infall is about that predicted by ΛCDM (see Figure 4).

Gas outflows

One of the key goals of the VLT LBG survey has been to investigate the presence of galaxy outflows at $z \approx 3$. As discussed earlier, a key piece of evidence for the presence of outflows is the velocity offset between Lyα emission and ISM absorption lines (e.g., C II, O II, Si IV). Figure 5 shows the histogram of redshift differences between the Lyα emission line redshifts and the interstellar absorption line redshifts. There is evidence of a significant offset in the sense that the Lyα line is blue-shifted with respect to the interstellar lines. We have therefore confirmed the results of the Keck group

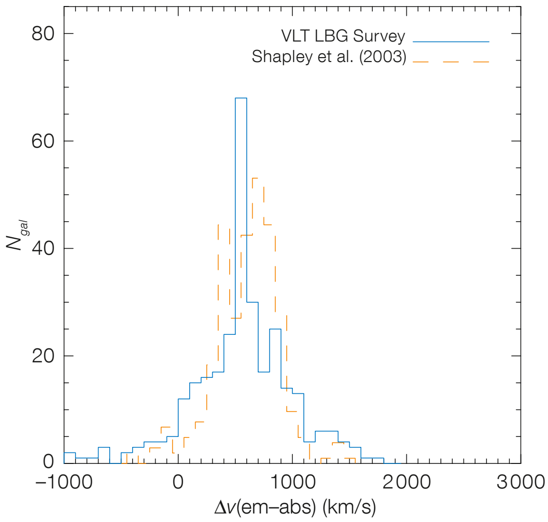

Figure 5. Velocity offsets between the Lyα emission line and the ISM absorption lines in the VLT LBG sample. The Lyα emission lines are redshifted relative to the ISM absorption lines, providing direct evidence for gas outflows from the star-forming galaxies at $z \approx 3$. Our VLT results agree with those from the Keck (Shapley et al., 2003).

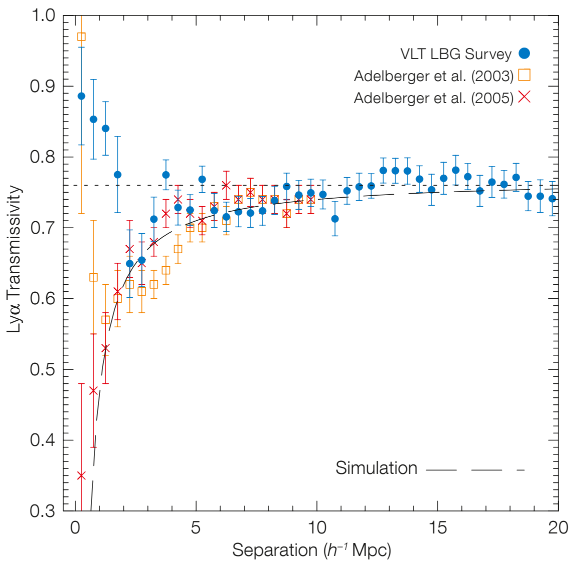

Figure 6. Average Lyα transmissivity as a function of distance from a $z = 3$ galaxy. Blue points show our results. Orange crosses and asterisks show results from Adelberger et al. (2003) and (2005) respectively. All datasets show a decrease in transmissivity (i.e. increased absorption) within 5 h^{-1} Mpc of an LBG, similar to the prediction from a hydrodynamical galaxy formation simulation. At smaller separations (< 2 h^{-1} Mpc) the rise in transmissivity in our VLT data provides evidence for star formation feedback. Outflows from star-forming galaxies may be heating the surrounding gas, preventing further star formation. We note that this is highly preliminary however and further data will beadded to this measurement from our latest VLT observations.

on this basic question about star-forming galaxies at $z \approx 3$.

Building on this result, we then performed a cross-correlation of the LBG sample with the underlying neutral hydrogen gas density as probed by QSO sightlines, based on the method of Adelberger et al. (2003, 2005). By tracing the relationship between gas and galaxies using cross-correlation analysis, we can find the extent of outflows around high redshift galaxies. We confirmed (Crighton et al., 2010) that as you get closer to an LBG (< 5 h^{-1} Mpc), the neutral hydrogen Lyα absorption in the forest increases (see Figure 6). We also improved the modelling of the Lyα cross-correlation function by studying the effect of LBG peculiar velocities and redshift errors on the gas–galaxy cross-correlation function. These can be quite sizeable since the LRIS/VIMOS velocity error is ~ 300 km/s or 3 h^{-1} Mpc. Nevertheless, in our latest results, with the full sample of 2100 LBGs, at separations below 1–2 h^{-1} Mpc the transmissivity increases again in a manner more like the result of Adelberger et al. (2003), rather than the Adelberger et al. (2005) result. This is direct evidence of the presence of galaxy formation feedback on the intergalactic medium immediately surrounding the galaxy, in line with the results shown in Figure 5. Peculiar velocities and measurement errors may contribute to the scale affected by feedback apparently extending to several megaparsecs in Figure 6.

Future work

Analysis of the VLT LBG survey is still continuing. On the galaxy evolution side, an immediate aim will be to analyse the redshift distortions in the LBG–Lyα cross-clustering in Figure 5 to understand better gas infall and outflows from galaxies. Fainter Lyman-α-emitter (LAE) galaxies have also been observed at $z = 3$ in all our fields via narrowband observations at the Subaru 8-metre, the CTIO 4-metre and the ESO 2.2-metre telescopes — these will allow the effect on the intergalactic gas of star formation in fainter galaxies to be measured. Further into the future, we want to determine better redshifts for the galaxies from nebular lines such as Hα in the near-infrared. The new VLT spectrograph KMOS (Sharples et al., 2010) should be ideal for this task and the KMOS integral field units will also afford dynamical information about the brighter targets.

There are also proposals to extend the cosmological aspects of the survey. Here the main aim will be to measure the baryon acoustic oscillations scale at $z \approx 3$ and test for evolution of the dark energy equation of state. This will require a formidable increase in survey size — more than an order of magnitude — but might still be feasible as a VIMOS large programme. Such a survey of around 25 000 LBGs could also be used to analyse redshift-space distortions and make a new cosmological test by looking for deviations from the spherical symmetry of LBG clusters in the redshift and angular directions in order to make a further basic test of cosmological models.

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