Studying the Properties of Early Galaxies with the ESO Remote Galaxy Survey

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We present a discussion of and results from the ESO Remote Galaxy Survey (ERGS), a spectroscopic survey of Lyman-break galaxies with $z \sim 5$ and above. The survey directly explores the properties of these early star-forming galaxies, increasing the observational detail in our picture of early galaxy evolution. The survey provides a sample of galaxies ideally matched in spatial distribution to the capabilities of current and imminently available instrumentation. We discuss the results of the first follow-on studies of the sample in the mm/sub-mm that signpost the potential of these facilities for exploring early galaxy evolution.

Over the last decade, the observational frontier of galaxy evolution research has been pushed back from two billion years after the Big Bang (at redshifts $z \sim 3$) to one billion years or less (at $z \sim 5$ and higher). While the difference in the cosmological time between these redshifts may seem insignificant, it is thought that during this early epoch the most massive galaxies in the local Universe underwent their first significant star formation episode. If this is so, what physical mechanisms drove this early collapse of galaxies and their first major episodes of star formation?

Much of our progress in developing understanding of the nature of galaxies in the early Universe has been made possible by extending the Lyman-break technique pioneered by Steidel and collaborators at $z \sim 3$ to higher redshifts. This photometric technique is, in principle, very efficient at identifying galaxies in the early Universe, but one must always be cautious of potential contamination by interloping lower redshift galaxies or stars that have similar red colours, and of the broad distribution in redshift inherent in such selection techniques. Both of these problems potentially undermine conclusions based on purely photometric samples — spectroscopic confirmation is crucial to remove contaminants, to investigate the clustering properties of galaxies and to understand the nature of their line emission. Perhaps most importantly, spectroscopic confirmation of regions with a large number of sources at similar redshifts enables detailed and efficient follow-up using facilities with comparatively small fields of view or limited spectral coverage. It is through the study of spectroscopically-confirmed samples well-matched to the capabilities of upcoming facilities that we will make progress in understanding the nature of the earliest galaxies.

In order to assemble a reliable sample of $z \sim 5$ Lyman-break galaxies (LBGs) that can be explored in detail at multiple wavelengths, we have carried out the ESO Remote Galaxy Survey (Douglas et al., 2007; 2009; 2010), building on our earlier work (e.g., Lehnert & Bremer, 2003; Stanway et al., 2004). In addition to determining the properties of both individual galaxies and the sample as a whole, we wanted to explore whether and how the galaxies cluster in three dimensions, as might be expected if they are the progenitors of massive galaxies at lower redshifts. Our previous analysis of $z \sim 5$ LBGs (Verma et al., 2007) showed that their stellar mass surface densities were extremely high, comparable to those found at the centres of massive galaxies today, lending support for this possibility.

The need to trace any clustering constrains observations to a high surface density of spectroscopically-confirmed sources, using multiple spectroscopic masks on a single field if necessary. This approach also has a clear benefit for follow-up studies with current and future instruments that have a limited field of view, where maximising the number of targets per pointing improves the scientific return of each observation. We also wanted to draw sources from multiple equatorial fields. Not only does this allow exploration of and mitigation of cosmic variance, but also has the practical effect of helping to avoid the RA-congestion inherent in concentrating any follow-up observations of only a few comparatively large public fields.

The ESO Remote Galaxy Survey large programme

Our large programme targeted ten fields previously imaged with FORS2 by the ESO Distant Cluster Survey (EDisCS) survey (White et al., 2005; Poggianti et al. 2009) in the *V*-, *R*- and *I*-bands and supplemented this with further imaging in the *z*-band. Although we have obtained imaging in longer wavebands for these fields, only the optical imaging data was used to select potential LBGs with $z \sim 5$ and above. Simple colour cuts (most importantly $R–I > 1.3$ mag) along with an *I*-band magnitude cut of $I_{AB} = 26.3$ were used to identify prime candidate LBGs, but where the available space on spectroscopic masks allowed, even these criteria were relaxed. The colour cut and *I*-band magnitude limit were chosen to select galaxies with $z > 4.8$ and to probe to luminosities the equivalent of one magnitude below L^* for $z \sim 3$ LBGs, thus allowing us to measure possible evolution in the UV luminosity function.

Our observing strategy enabled the widest range of candidate LBGs to be targeted by spectroscopic follow-up, minimising the number of true $z \sim 5$ galaxies rejected from our sample before spectroscopy. The number of spectroscopic masks used on any one field was guided by the number of photometric candidates in that field, varying from one mask for the poorest to five masks for the richest field. Objects were prioritised for spectroscopy using the multi-wavelength data in each field, but given the number of masks, completeness was generally very good. This approach, coupled with the liberal selection technique generally maximised the surface density of spectroscopically-confirmed LBGs in the fields. In addition, given the relatively high completeness of this approach, we are able to use the spectroscopically-confirmed sample to infer the global statistical properties of the set of objects that either were untargeted spectroscopically or failed to yield a reliable redshift, despite being subjected to spectroscopy.

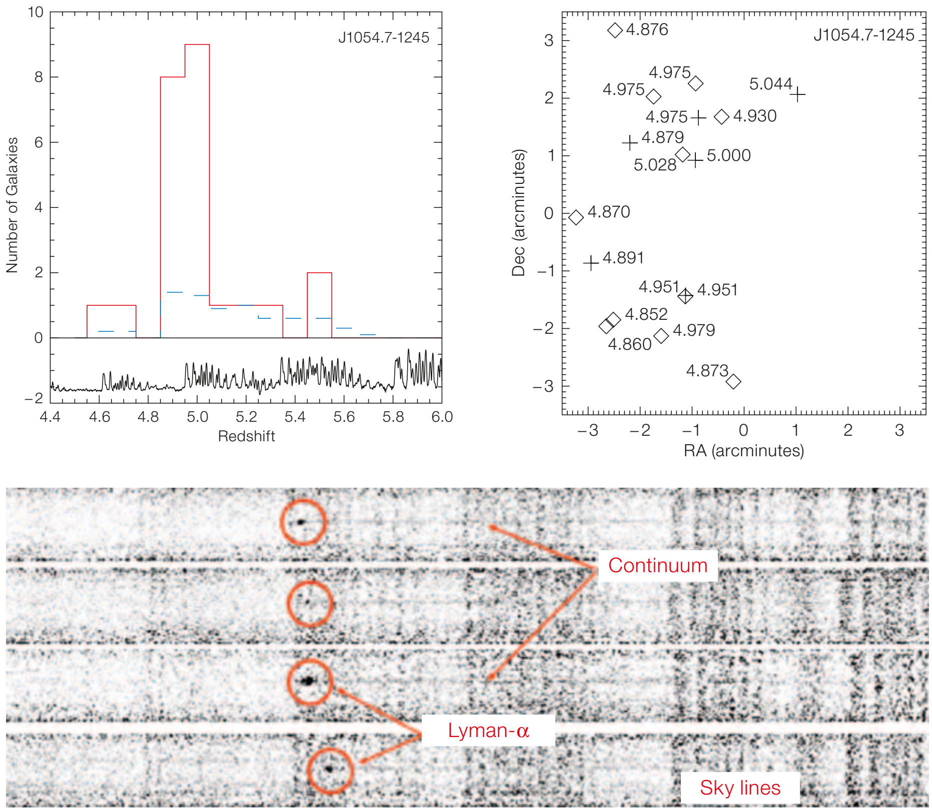

Figure 1. The redshift distribution of spectroscopically confirmed LBGs in one ERGS field, J1054-1245, is shown at upper left (in red) in comparison to the distribution of redshifts in the survey as a whole, normalised to the same area (in blue). The redshift "spike" at $z \sim 5$ is obvious. The night-sky strength as a function of redshift for Lyα is shown below the redshift distribution. The spatial distribution of the LBGs in this redshift spike across the FORS2 imaging field is shown at upper right. Four examples of two-dimensional spectra of LBGs in the spike are shown (lower plot). In each case wavelength increases to the right and position along the slit varies vertically. Objects show clear Lyα emission and continuum redward of the line.

We carried out FORS2 spectroscopy using twenty masks across the ten fields (totalling an effective area of about 450 square arcminutes), resulting in a sample of some 70 spectroscopically-confirmed LBGs at $z \sim 5$ and above. Approximately half of the spectra show Lyα emission plus a continuum break, the rest only a break in the continuum as the intervening intergalactic medium (IGM) scatters the continuum shortwards of restframe Lyα out of our line of sight. The objects are not distributed uniformly across the fields. Two fields in particular show clear three-dimensional clustering of LBGs; not only do the sources cluster spatially, their redshift distributions show clear "spikes" at particular redshifts, unlike the typical field (see Figure 1). The LBGs within these fields trace out coherent large-scale structures, not necessarily proto-clusters, but more likely rich sheets or filaments of matter seen when the Universe was approximately one billion years old. The density of LBGs within these structures makes them particularly suitable targets for follow-up studies with comparatively small-field future instrumentation such as ALMA and KMOS.

While this kind of structure in the LBG distribution might be expected if it were to eventually form massive galaxies, the structures are physically very extended and the LBGs must inhabit separate dark matter halos. This large scale, when taken together with the comparatively short-lived nature of typical $z \sim 5$ LBG starbursts (a few tens of Myr, Verma et al., 2007), make it unlikely that all the LBGs in the structure will eventually combine to form a single massive galaxy (or several such galaxies). For these to form, most of the baryons within them cannot be within the UV luminous LBGs at $z \sim 5$. The LBGs may trace regions where these reside, either in separate systems within the same large-scale structure, or in larger underlying galaxies within which the UV-luminous LBGs are embedded. The LBGs may well be the UV-luminous "tip of the iceberg" of a much larger over-dense structure, whether a sheet, filament or perhaps proto-cluster. This issue motivates our mm/sub-mm follow-up of these fields, discussed below.

Our spectroscopy is complete enough, and the likely contamination fraction of non $z \sim 5$ sources in the spectroscopically unconfirmed subsample is sufficiently well understood that we can explore the distribution of Lyα equivalent widths in $z \sim 5$ LBGs. This distribution is an indicator of the underlying initial mass function (IMF) within the ongoing starburst that powers the UV emission from the LBGs. There has been recent discussion in the literature as to whether higher redshift systems have top-heavy IMFs (with a high ratio of massive to low-mass stars) as they may have restframe UV colours too blue for a standard IMF. Higher Lyα equivalent widths favour top-heavy IMFs. The distribution of equivalent widths for the spectroscopically-confirmed $z \sim 5$ sources is biased to higher values than the similar distribution for $z \sim 3$ LBGs. However, because of our careful assessment of the completeness and reliability of our sample, we can correct for the contribution of spectroscopically-unconfirmed $z \sim 5$ sources, which by definition have low or negative Lyα equivalent widths. When this is done, the $z \sim 5$ distribution is consistent with that seen at $z \sim 3$; there is no evidence for an evolution in the IMF between these redshifts.

The spectroscopy also reveals a difference between the restframe UV-optical spectral energy distributions of the line-emitting and the break-only populations. The break-only galaxies appear to have both redder observed I–K colours and redder 1200–1700 Å restframe continuum slopes than the line-emitters, a difference that is difficult to explain purely by differences in the ages of their stellar populations. Allowing the metallicity or dust extinction to vary between these two subsamples may explain the difference, with the break-only subsample being more extincted and/or having a slightly higher metallicity. Taken as a whole, if the correlation between metallicity and UV continuum slope identified at low redshift is applicable at

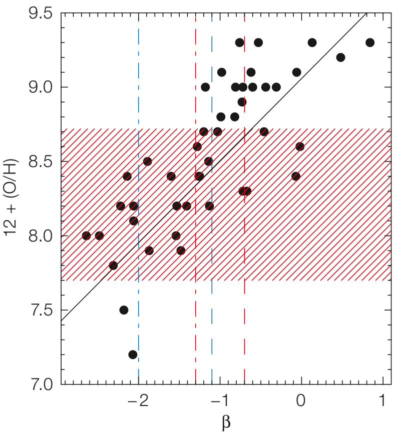

Figure 2. A plot of metallicity against UV spectral slope, β. Points show the correlation between the quantities for local galaxies (from Heckman et al., 1998). The dot-dashed vertical lines indicate the spectral slope of the galaxies with only spectral breaks (no line emission) in our sample (red) and for the whole sample with spectroscopic redshifts (blue), and the dashed vertical lines indicate the spectral slope of the galaxies with Lyα mostly in absorption (red) and galaxies with Lyα predominately in emission (blue) for LBGs at $z \sim 3$ (Shapley et al., 2003). Our objects appear to have steeper UV spectra than $z \sim 3$ LBGs, indicating lower typical metallicities, on average 0.3 $Z_{\odot}$, but with some scatter. The red hatched area indicates the range of metallicity estimates in prior literature.

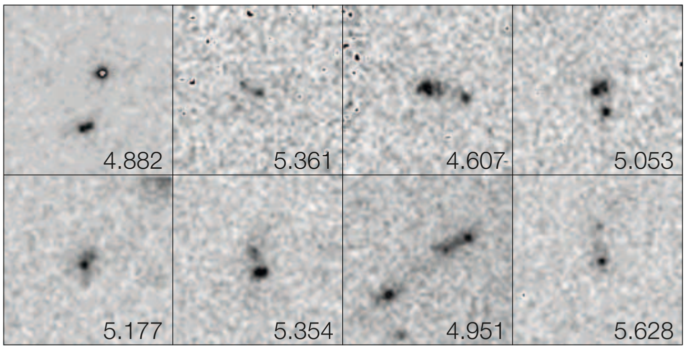

Figure 3. Eight examples of spectroscopically confirmed galaxies with multiple components. Each box is 5 arcseconds × 5 arcseconds and the images were taken using the HST/ACS camera and the F814W filter. Redshifts are indicated in the bottom right-hand corners.

$z > 3$, the typical $z \sim 5$ LBGs have metallicities a factor of ~ 3 lower than those of LBGs at $z \sim 3$ (see Figure 2), a result consistent with that found in a photometric study of the GOODS–South LBGs by Verma et al. (2007).

Most of the EDisCS fields have been imaged in the restframe UV by the Hubble Space Telescope (HST). Many of the LBGs, both the candidates from the photometric sample and the spectroscopically confirmed objects, are imaged at kiloparsec-scale resolution. A majority of the spectroscopically confirmed objects covered by this imaging are resolved on this scale into two or more UV luminous components, while being unresolved in the ground-based imaging (typically corresponding to a scale of order ~ 10 kpc, see Figure 3). There has been some debate in the literature as to the nature of LBGs, particularly those with multiple UV components. Could these systems be UV-luminous super-star clusters embedded in individual, mostly obscured, more massive systems, or could they be indicative of merger events, potentially with each component being a complete system undergoing the merger? The nature of the larger-scale clustering seen in some of the fields might support the "embedded" hypothesis in order to account for sufficient baryons to form massive galaxies at lower redshifts. However, work on nearby analogues of LBGs (Overzier et al., 2008) indicates that, for these low redshift systems at least, the merger hypothesis is most likely. It is impossible to determine whether either of these scenarios account for the structure seen in the $z \sim 5$ systems from the optical imaging and spectroscopy data alone. However, this is exactly the type of issue that ERGS was designed to tackle through follow-up observations in other wavebands.

ERGS in other wavebands

Our first steps in following up ERGS have been carried out in the mm and sub-mm, in order to answer several questions raised by our optical and near-infrared results from the VLT. The mm and sub-mm allows us to trace cold molecular gas and dust. Since this is the material out of which stars form, ascertaining the amount of cold gas will allow us to, for example, determine the potential for these galaxies to keep forming stars. This also had the additional benefit of enabling us to prepare for future observations with ALMA.

We chose to follow up the two most clustered fields. Not only does this allow us to observe and characterise a comparatively large number of LBGs in relatively few deep pointings, but it has also allowed us to search for other non UV-luminous sources embedded in the same large-scale structures as the LBGs, as might be expected if these they are truly the progenitors of massive galaxies. Our initial exploration in these wavebands have used LABOCA on APEX to image one field in continuum at 870 μm (about 150 μm in the restframe) and the Australia Telescope Compact Array (ATCA) to image two fields at 7 mm and 12 mm to search for redshifted CO(2–1) and CO(1–0) line emission respectively. The latter observations can be thought of as less sensitive and lower frequency pathfinders to future ALMA studies, with ALMA being able to target the same fields at higher frequencies, probing higher transitions of CO and potentially the key [C II] line which is the dominant coolant of the interstellar medium, amongst other lines.

The sub-mm observations with LABOCA (Stanway et al., 2010) targeted a field containing twelve spectroscopically-confirmed $z \sim 5$ LBGs. Ten lay in a region where the data had a 2σ limit of 3 mJy. To this level, no individual LBG was detected. Stacking the pixels corresponding to these $z \sim 5$ galaxies, a limit of < 0.85 mJy was placed on the 870 μm emission of the "average" $z \sim 5$ LBG. With an assumed dust temperature of 30 K, this places a limit on the typical dust mass of below $1.2 \times 10^8\ M_{\odot}$, no more than ~ 10 % of the stellar mass of the typical system. Higher temperatures lead to even lower masses. Future ALMA observations, will be orders of magnitude more sensitive, and thus individual galaxies are likely detectable in relatively short exposures.

The ATCA observations (Stanway et al., 2008; Davies et al., 2010) similarly targeted multiple LBGs in two clustered ERGS fields. No individual galaxy was detected in either CO(2–1) or CO(1–0). After stacking the spectra of eight LBGs in one field, we found a limit to the molecular gas content of the average $z \sim 5$ LBG of $< 3.1 \times 10^9\ M_{\odot}$.

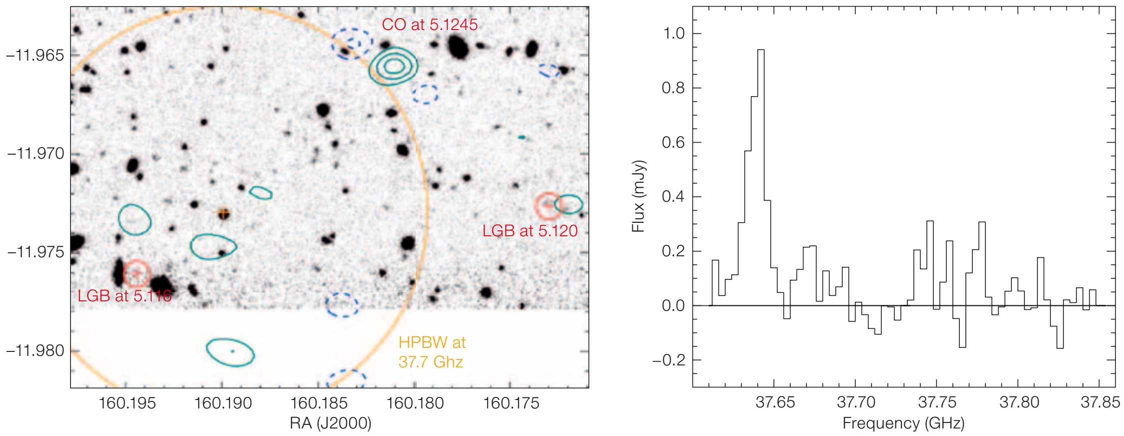

Figure 4. *I*-band image of part of one of our fields is shown (left) containing two LBGs at $z = 5.12$, indicated by the red circles with crosses inside, overlaid with (green) contours of radio emission at frequencies corresponding to the CO(2–1) line at the same redshift as the LBGs. An object with no obvious optical counterpart is detected at these frequencies close to the top of the image. The field centre and half-power beam width of the ATCA radio observations are indicated by the yellow cross and circle respectively. The 37.7 GHz-band ATCA spectrum of the source detected in the radio data, indicating a clear line at a frequency consistent with CO(2–1) at $z = 5.1245$, is shown at right.

This limit is comparable to the stellar mass of a typical source. Given the low conversion rate of molecular gas into stars, these systems are running out of fuel for their ongoing starburst; they are being observed a substantial way through and probably close to the end of the event. This agrees with previous determinations of the typical ages of the stellar populations of these sources and our own LABOCA results.

Taken together, these observations indicate that $z \sim 5$ LBGs are unlikely to be UV-luminous super-star clusters embedded in larger, more heavily obscured underlying systems, as these should have been detected in the mm/sub-mm observations. Consequently, they give strong support to the idea that the $z \sim 5$ LBGs are "switched on" by mergers and the resulting starburst uses up (or expels through driving strong winds) the available fuel, typically in a few tens of millions of years. The bias to observing the galaxies towards the end of the starburst phase would be a natural consequence of the merger trigger. Provided that the starburst lasts a length of time comparable to, or shorter than, the lifetimes of massive stars, we would only ever expect to predominantly select sources at the end of their starburst in a restframe UV-luminosity selected sample.

The data also indicate that the over-dense structures traced by these LBGs do not contain a large population of mm/sub-mm luminous starbursts. In the LABOCA field, there is a single convincing detection of a source away from the area covered by our optical imaging, consistent with the number of detections found in observations of other fields to the same depth. No excess of sub-mm sources associated with the structure traced by LBGs are detected within the current dataset. While deeper observations with ALMA and other facilities will likely detect less luminous systems within such structures, the current observations do not indicate a significant association of the most luminous sub-mm galaxies with over-densities of LBGs at $z \sim 5$. In the single case where we have detected (Stanway et al., 2008, see Figure 4) and subsequently reconfirmed (Stanway et al., 2010, in preparation) CO emission from a galaxy embedded in the same structure as multiple LBGs, the ratio of CO to continuum luminosity indicates that the starburst within that galaxy is closer in nature to luminous starbursts seen in low redshift spiral galaxies, rather than to the ultra- or hyper-luminous sources selected in the sub-mm at intermediate and high redshifts.

Prospects

The ESO Remote Galaxy Survey has given us important clues about the nature of galaxies seen 1 Gyr after the Big Bang. ERGS has shown that $z \sim 5$ LBGs are young, relatively metal-poor, compact intense starbursts, apparently in the throes of merging, and which trace out large coherent structures. The key to obtaining this knowledge was the spectroscopic observations with FORS2 that allowed us to estimate contamination rates, determine if the galaxies had a top-heavy IMF, investigate their clustering properties and enabled us to make important follow-up observations with other facilities.

These initial follow-up studies of ERGS give an indication of the work on the most distant galaxies that will be made possible with future facilities. Rather than studying potentially atypical luminous sources, facilities such as ALMA and the E-ELT will allow us to study the more numerous and typical populations in all of their gaseous phases, from cold molecular to warm/hot ionised gas, and provide spectral energy distributions from the restframe UV out to the sub-mm. Such targeted observations will characterise the $z \sim 5$ LBGs (and by extension higher redshift systems) in the greatest detail along with other, as yet undetected, galaxies sharing the same structures. Fields containing a high density of spectroscopically-confirmed high redshift sources, such as those in ERGS, are the ideal targets for a detailed investigation of the early evolution of galaxies with the VLT and future facilities such as ALMA and the E-ELT.

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