Number counts and clustering properties of bright Distant Red Galaxies in the UKIDSS Ultra Deep Survey Early Data Release

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Abstract

We describe the number counts and spatial distribution of 239 Distant Red Galaxies (DRGs), selected from the Early Data Release of the UKIDSS Ultra Deep Survey. The DRGs are identified by their very red infrared colours with $(J - K)_{AB} > 1.3$, selected over $0.62 \text{deg}^2$ to a $90\%$ completeness limit of $K_{AB} \simeq 20.7$. This is the first time a large sample of bright DRGs has been studied within a contiguous area, and we provide the first measurements of their number counts and clustering. The population shows strong angular clustering, intermediate between those of $K$-selected field galaxies and optical/infrared-selected Extremely Red Galaxies. Adopting the redshift distributions determined from other recent studies, we infer a high correlation length of $r_0 \sim 11 \, h^{-1}\text{Mpc}$. Such strong clustering could imply that our galaxies are hosted by very massive dark matter halos, consistent with the progenitors of present-day $L \gtrsim L_\ast$ elliptical galaxies.

Key words: galaxies: high-redshift – cosmology: observations – galaxies: evolution.

1 INTRODUCTION

A new near-infrared selection technique has been developed in recent years to sample galaxies in the high-redshift Universe. By relying on purely near-infrared colours, this potentially avoids many biases which are inherent in optical techniques, particularly for detected dusty and/or evolved galaxies. Franx et al. (2003) argue that the simple $(J - K)_{AB} > 1.3$ colour selection criteria produces a sample that is mainly populated by galaxies at $z > 2$, at least at faint $K$-band magnitudes ($K_{AB} \gtrsim 21$). These are the so-called Distant Red Galaxies (hereafter DRGs). In the Faint Infrared Extragalactic Survey (FIREs), Franx et al. (2003) selected 14 candidate galaxies at $z > 2$ to a depth of $K_{AB} < 24.4$, of which 6 were spectroscopically confirmed. Van Dokkum et al. (2003), Labbé et al. (2005) found that approximately $70\%$ of DRGs are dusty star forming galaxies and the remaining $30\%$ are passively evolved galaxies.

Work by Rudnick et al. (2003) suggest that DRGs may be a significant constituent of the $z \sim 2 - 3$ universe in terms of stellar mass. Förster Schreiber et al. (2004) demonstrated that the average rest-frame optical colours of DRGs fall within the range covered by normal galaxies locally, unlike the Lyman-break galaxies (LBGs – Steidel et al. 1996) which are typically much bluer. Larger samples of DRGs covering a wide range in stellar mass are now required to fully understand the importance of this population. In particular, studies conducted so far have (by necessity) concentrated on DRGs selected over relatively small areas, and very little is known about the bright end of this population.

In terms of stellar mass, metallicity and star formation rate Reddy et al. (2005) find strong similarities between optically-selected and near-infrared selected galaxy samples. Clustering offers an alternative way to to study these populations. At large scales, the galaxy distribution is dominated by dark matter halo clustering, which is a strong function of halo mass. Several studies have measured strong clustering strength for high redshift galaxies selected in the near-infrared $(r_0 = 10 - 15h^{-1}\text{Mpc})$. Daddi et al.
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2003 [Grazian et al. 2006], comparable to the most luminous galaxies in the local universe.

In this paper we present a study of the first large sample of DRGs selected at bright infrared magnitudes \(K_{AB} < 21\) in a contiguous area. We analyse the number counts and clustering and draw conclusions about their likely origin. Throughout this paper, we assume \(\Omega_m = 0.3\), \(\Omega_{\Lambda} = 0.7\) and \(h = H_0/70\) km s \(^{-1}\) Mpc \(^{-1}\).

2 UKIDSS UDS EARLY DATA RELEASE

2.1 Survey and Early Data Release

The UKIRT Infrared Deep Sky Survey (UKIDSS – Lawrence et al. 2006) is based on observations in Spring 2005, using the Wide-Field Camera (WFCAM – Casali et al., in prep.) at the 3.8-m United-Kingdom InfraRed Telescope (UKIRT). Comprising 5 sub-surveys, it will take 7 years to complete and will cover a range of areas and depths. The deepest of these 5 sub-surveys, the Ultra-Deep Survey (UDS) aims to cover 0.8 deg\(^2\) to a depth of \(K_{AB} = 25.0\), 
\(H_{AB} = 25.4\), 
\(J_{AB} = 26.0\) (5\(\sigma\), point-source). It is centred on the Subaru/XMM-Newton Deep Survey field (SXDS – Sekiguchi et al. 2005) at \(02^h 18^m 00^s\), \(-05^\circ 00' 00''\) (2000).

Since February 10 2006, the UKIDSS Early Data Release (EDR) has been available to the ESO community. A full description of this data release is given in [Dye et al. 2006].

2.2 Image stacking and mosaics

The stacking of the UDS EDR data was performed by our team using a slightly different recipe to the standard UKIDSS pipeline. The final mosaiced images in the local universe.

2.3 Catalogue extraction

We found that the standard UKIDSS source detection software did not produce optimal catalogues for the UDS. We therefore produced a much improved catalogue for the EDR by using the SExtractor software ([Bertin & Arnouts 1996]). The \(K\)-band image was used as the source detection image, since this is measurably deeper for most galaxy colours. All \(K_{AB}\) magnitudes quoted below are total magnitudes extracted using the SExtractor parameter MAG_AUTO, while all colour measurements are obtained from fixed 2'' aperture magnitudes.

To optimise our catalogue extraction we performed a series of simulations to fine tune the SExtractor parameters. Artificial point-like sources were added to the real \(K\)-band image using the observed PSF with FWHM = 0.69'' (rejecting regions containing bright sources), and distributed with magnitudes in the range \(14 < K_{AB} < 24\). From the resulting new image a catalogue was extracted using SExtractor and compared with the list of artificial source positions. This process was repeated 1000 times, and the resulting statistics allow us to estimate the catalogue completeness and the evolution of photometric errors. Using these simulations, SExtractor detection parameters were tuned to maximise completeness at the noise-determined 5\(\sigma\) depth of \(K_{AB} = 22.5\), while simultaneously minimising the number of spurious sources. While formally optimised for point-like sources, we note that these were close to optimal when we generated artificial sources using a substantially more extended PSF (FWHM = 1.2\(''\)).

Using these parameters, we extracted 78709 sources over 0.62deg\(^2\) from the image, of which 34098 were determined to be unsaturated, unmasked and from regions of uniform coverage to \(K_{AB} < 22.5\). These form the basis of the analysis outlined below. Assuming the background noise is symmetric about zero, we can estimate the spurious fraction by extracting sources from the inverted image and comparing with the number of sources extracted from the normal image. At our magnitude limit of \(K_{AB} = 22.5\) the fraction of spurious detections is found to be less than 1%, while the completeness level is above 70% (for point sources).

3 SELECTION AND NUMBER COUNTS

3.1 Selection of DRGs

From the catalogue described above we selected objects using the \((J - K)_{AB} > 1.3\) criteria. A visual inspection of each source was then required to remove spurious detections, which at these extreme colours was found to be a relatively large fraction (~20%). The majority are caused by diffraction spikes and cross-talk images ([Dye et al. 2006]) and are easy to identify and reject. This leaves 369 DRGs at \(K_{AB} < 21.2\), which represents the largest sample selected over a contiguous area. The surface density derived is \(n = 0.163 \pm 0.009\) arcmin\(^{-2}\). Figure [1] shows the \((J - K)\) colour of these galaxies versus \(K\)-band magnitude. The object shown by a star was classified as a point-like source in our global catalogue, and is confirmed to be a star after visual inspection.
3.2 Photometric errors and contamination of DRG sample

Since our sample is based on \((J - K)\) colour selection it is vital to carefully consider the effects of photometric errors. Since most galaxies show substantially bluer colours (Figure 1) we can expect the number density of DRGs to be artificially boosted at fainter magnitudes, as errors push objects above the crude boundary between galaxies and the stellar locus at \((J - K) = 0\). As a lower limit to this contamination we could use the photometric errors derived from SExtractor, and these are shown as a function of magnitude in Figure 1. Our experience suggests that analytically-determined errors from SExtractor are likely to be underestimates, so we use the mean photometric errors obtained from the simulations described in section 3.3.

We used our simulated errors to estimate the contamination by randomising the real galaxy catalogue using Monte-Carlo simulations. For each object in our full catalogue, we allow the \((J - K)\) colour to vary assuming a Gaussian distribution with a standard deviation corresponding to the chosen photometric error. We then re-select our catalogue using the \((J - K)_{\text{AB}} > 1.3\) criteria, and repeat this process 1000 times. This should provide an approximate upper limit on contamination, since we are randomising the observed galaxy catalogue (which already suffers from the effects of photometric errors).

Defining the contamination fraction from the number of objects scattered into our selection boundary minus those which are scattered out, our simulated source errors yield contamination fractions of \((46.0 \pm 3.8)\%\) at the limiting magnitude of \(K_{\text{AB}} < 21.2\), falling to \((16.8 \pm 3.6)\%\) at \(K_{\text{AB}} < 20.7\) (the estimated completeness limit; see Section 3.3). We note that the typical error on the colour is \(\Delta(J - K)_{\text{AB}} \sim 0.1\) at \(K_{\text{AB}} = 20.7\). As shown in Conselice et al. (2006), a slight change of the \((J - K)\) colour selection does not have a major affect on the redshift distribution.

Based on these values we conclude that our number counts and clustering measurements are reasonably robust at \(K_{\text{AB}} < 20.7\), but will become increasingly unreliable at fainter magnitudes. We will therefore adopt a limit of \(K_{\text{AB}} = 20.7\) for further study, which produces a sample of 239 DRGs.

3.3 Number counts of DRGs

Figure 2 shows the \(K\)-band differential number counts of our sample of DRGs. The number counts indicate that our sample is complete up to approximately \(K_{\text{AB}} \sim 20.7\), after which the counts are clearly dropping. This defines our estimated completeness limit. Our simulations suggest that the contamination due to photometric errors will be \(~ 16\%) at \(K_{\text{AB}} < 20.7\). We conclude the dominant source of error in our number counts will be Poisson counting errors (plotted) and cosmic variance (discussed in section 3.4).

At bright magnitudes (e.g. \(K_{\text{AB}} < 20\)) our UKIDSS data are entirely unique, and no studies exist in the literature for comparison. At fainter magnitudes, our counts are in very good agreement with the DRG counts from the Grazian et al. (2006) sample. They are also consistent with the number counts from the AEGIS survey (Foucaud et al. in prep.; see also Conselice et al. 2006). Combining literature data with the present work we can examine the global shape of the DRG number counts over a very wide dynamic range \((18.5 < K_{\text{AB}} < 25.0)\). This strongly suggests a break feature in the slope at \(K_{\text{AB}} \sim 20.5\) which is an effect already seen in the global K-band number counts (e.g. Gardner et al. 1993).

We note that the projected density of DRGs is approximately 10 times lower than EROs, and approximately 100 times lower than the global galaxy counts at a given magnitude.
3.4 Cosmic variance

As a simple test of cosmic variance, and to investigate whether the UDS is an unusual field, we used the data available from the UKIDSS Deep Extragalactic Survey (DXS) to perform a comparison study. The DXS is the other deep extragalactic component of UKIDSS (Lawrence et al. 2006), consisting of 4 fields with a 7-year goal of observing 35 deg$^2$ to depths of $K_{AB} = 22.7$ and $J_{AB} = 23.2$. We used data from 3 fields observed in both $J$- and $K$-bands in the UKIDSS EDR, covering $\sim 2900$ arcmin$^2$, $\sim 4500$ arcmin$^2$ and $\sim 2900$ arcmin$^2$ respectively. While exposure times are similar to the UDS EDR, the observing conditions are generally poorer. Direct comparison is also complicated by the different source extraction methods used by the DXS.

We applied the same selection method described in section 3.1 except that we did not visually inspect the samples. This selects 1523 objects in total, of which we estimate approximately 20% are likely to be spurious (see section 3.1), with a similar fraction likely to be artificially boosted due to photometric errors at faint magnitudes (section 3.2). Since these errors are smaller than the errors in the DXS counts, for simplicity we opt not to make these corrections in our comparison with the UDS. We derived a median surface density of $n = 0.176 \pm 0.075$ arcmin$^{-2}$ at $K_{AB} = 21.2$, in very good agreement with the UDS value.

The resulting median counts from the 3 DXS samples are overplotted in figure 2 with errors representing the field-to-field RMS variance. The agreement with UDS is very good. Although no corrections were applied, this crude comparison suggests that the density of DRGs is stable and broadly consistent between fields.

4 THE CLUSTERING OF DRGs

4.1 Angular clustering

In Figure 2 we display the distribution of our sample of DRGs on the sky. Visually the DRGs appear strongly clustered. As a more quantitative measure, we evaluate the 2-point angular correlation function, cutting our sample at $K_{AB} = 20.7$ as before.

4.2 Spatial correlation lengths and biasing

In order to compare the clustering of galaxy populations at different redshifts we must derive spatial correlation measurements. Assuming a redshift distribution for our sample we can derive the correlation length and a linear bias estimation using the relativistic Limber
equation (Magliocchetti et al. 2000). The difficulty here is to have a realistic estimation of the redshift distribution of our sample. While Franx et al. (2003) have designed the \((J-K)_{AB} > 1.3\) criteria to select \(z > 2\) galaxies, Grazian et al. (2006) and Conselice et al. (2006) have shown that the redshift distribution is broad, and the fraction of \(z < 2\) galaxies increases at bright magnitudes.

As a preliminary investigation we assume a Gaussian form for the redshift distribution, fixing the mean and standard deviation to match recent studies of fainter DRGs. Analytical and fitted redshift distributions make no significant difference to our derived correlation lengths. The correlation length can then be evaluated if we fix the slope of the correlation function to \(\gamma = 1 + \delta = 2.0\). In the DRG sample of Grazian et al. (2006), a mean redshift of \(\bar{z} = 1.5\) was found at a limit of \(K_{AB} < 22.0\). Using this mean redshift with \(\sigma = 0.5\) (broadly matching their distribution) we determine \(r_0 = 11.0 \pm 3.3 \, h^{-1}\) Mpc and \(b = 4.0 \pm 1.4\) for our DRGs. Conselice et al. (2006) suggest that very bright DRGs lie at even lower redshifts. If we adopt the observed redshift distribution of their spectroscopic sample we derive \(r_0 = 7.4 \pm 2.4 \, h^{-1}\) Mpc and \(b = 4.0 \pm 1.4\), when the approximated gaussian form gives (with \(\bar{z} = 1.0\) and \(\sigma = 0.25\)) \(r_0 = 11.0 \pm 3.3 \, h^{-1}\) Mpc and \(b = 4.0 \pm 1.4\).

Grazian et al. (2006) also split their sample according to redshift, and found \(r_0 = 7.4 \pm 2.4 \, h^{-1}\) Mpc for DRGs at \(1 < z < 2\) with \(K_{AB} < 22\). Our sample is substantially brighter, so, even if the two samples are probing slightly different redshifts, our larger correlation length could be interpreted as evidence for luminosity segregation, in agreement with biased galaxy formation scenarios.

5 SUMMARY

We have extracted a large sample of bright Distant Red Galaxies from the UKIDSS UDS EDR. Our catalogue contains 369 DRGs to a limiting magnitude of \(K_{AB} = 21.2\), extracted over an area of 0.62 deg\(^2\). The fainter \(K_{AB} > 20.0\) number counts are in good agreement with previous estimates, while at brighter magnitudes the sample is unique. Using simulations we determined that contamination due to photometric errors is below \(\sim 16\%\) at an approximate completeness limit of \(K_{AB} < 20.7\).

From this sample we extracted a sub-sample of 239 bright DRGs to a limit of \(K_{AB} = 20.7\). These bright DRGs appear highly clustered, and we determine a correlation length of \(r_0 \approx 11 \, h^{-1}\) Mpc and a bias measurement \(b \approx 4.5\), assuming the sample lies at a mean redshift of \(\bar{z} = 1.0\) with a standard deviation of \(\sigma = 0.25\) (consistent with studies at similar depths – Conselice et al. 2006). They appear more clustered than fainter samples of DRGs derived at these redshifts, which may be evidence for luminosity segregation.

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