Completeness and confusion in the identification of Lyman-break galaxies

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Abstract.
We have carried out a study to simulate distant clusters of galaxies in deep ground-based optical images. We find that when model galaxies are added to deep images obtained with the William Herschel Telescope, there is considerable scatter of the recovered galaxy colours away from the model values; this scatter is larger than that expected from photometric errors and is significantly affected by confusion, due to ground-based seeing, between objects in the field. In typical conditions of \( \approx 1\text{-arcsec} \) seeing, the combination of confusion and incompleteness causes a considerable underestimation of the true surface density of \( z \approx 3 \) galaxies. We argue that the actual surface density of \( z \approx 3 \) galaxies may be several times greater than that estimated by previous ground-based studies, consistent with the surface density of such objects found in the HDF.

1. Introduction

The field of the of the \( z = 3.8 \) quasar pair PC1643+4631 A & B contains a Cosmic Microwave Background decrement (Jones et al. 1997) which may be the Sunyaev-Zel’dovich effect of a cluster of galaxies at \( z \gg 1 \) (Saunders et al. 1997; Kneissl et al. 1998). In an attempt to detect such a cluster, we have carried out deep UGVRI imaging of the field. No cluster is immediately obvious in the images, so we carried out Monte-Carlo simulations to quantify our ability to detect a cluster of galaxies in our images (full details are given in Haynes et al. 1999 and Cotter et al. 1999).

2. Model high-\( z \) cluster galaxies

Model clusters were created using simulated colours of evolving galaxies in the redshift range \( 0 < z < 4 \), and added to our WHT images. We then used photometric redshift techniques to try to recover the simulated cluster. As the cluster redshift reached \( z \approx 1 \) and beyond, the lack of strong spectral features in the optical made the cluster increasingly difficult to detect. However, even at \( z \approx 3 \), where the characteristic Lyman-limit break became detectable, a large
Figure 1. Recovered UGR colours of simulated $2.5 < z < 3.5$ cluster galaxies. All objects shown have measured $R < 25.5$ and $G > 2\sigma$. The triangles denote 1-$\sigma$ lower limits in $U-G$. The crosses are stars from the Gunn & Stryker (1983) database and the dot-dash line is our bound for selecting $z > 3$ candidates. The tracks show the simulated galaxy colours at various redshifts; the point at $U-G = 2.2$ and $G-R = 0.3$ corresponds to $z = 3.0$, and points at larger $U-G$ are at higher redshift in steps of $\Delta z = 0.1$. Note that the recovered colours are skewed towards the red in $G-R$.

fraction of the the fake cluster galaxies were still recovered from the simulation with ambiguous colours (Fig 1). Indeed, in our $z = 3.0$ simulation, only one in five of the model cluster galaxies was identified as such by UGR selection. The recovered colours were skewed towards the red in $G-R$; this is a result of confusion with other objects in the field.

3. Recovery of model $z \approx 3$ galaxies

Our original search for $z \approx 3$ Lyman-break galaxies (LBGs) in these images (Cotter & Haynes 1998) had recovered a reasonable number of candidates—approximately 1.1 arcmin$^{-2}$, similar to the findings of the surveys of Steidel et al. (1996,1998). The fact that our recovery of simulated high-$z$ cluster galaxies was so inefficient therefore prompted us to measure the effects of completeness and confusion specifically for $z \approx 3$ galaxies.

We ran 1000 simulations, each time adding ten fake LBGs to our images. Fake LBGs were drawn from a Schechter luminosity function with $R_* = 24$ and $\alpha = 1.06$; all had input colours $G - R = 2.2$, $U - G = 0.3$. We used input half-light radii of 0.2-0.3″ (Giavalisco et al. 1998).

Then, using FOCAS, we attempted to recover the LBGs. Our selection criteria are chosen to be as close as possible to that of Steidel et al. We select only those galaxies clearly detected with $R < 25.5$ above the 3-$\sigma$ isophote in $R$, measure magnitudes in $U$ and $G$ through this $R$-band isophote, and then impose
a colour cut of $U - G > 2, U - G > 4(G - R) + 0.5$, which is closely equivalent to the “robust” colour selection of Steidel et al. First, we find that 53% of galaxies with input $R < 25.5$ are selected to the isophotal $R = 25.5$ limit. Second, we find that, as for our fake cluster galaxies, a large fraction of the fake LBGs are scattered far away from their input colours.

In total, only 23% of the input LBGs with $R < 25.5$ remain within the $z \geq 3$ region of the $UGR$ plane (Fig 2). Therefore, the true number of LBG candidates in our images may be four times greater than the 1.1 arcmin$^{-2}$ we measure. Again we stress that, while our $UGR$ filter set is slightly different from the $U_nGR$ used by Steidel et al., our search for genuine LBG candidates in these images finds a surface density at least as great as that of Steidel et al.

Figure 2. Recovered colours of fake $z = 3.0$ LBGs; all have input colours $G - R = 2.2, U - G = 0.3$. All galaxies recovered to the $R = 25.5$ 3-$\sigma$ isophote are shown; crosses mark those outside the $z \geq 3$ region of colour-colour space defined by the solid line ($U - G > 2, U - G > 4(G - R) + 0.5$). Dots mark the 23% of the galaxies with input $R < 25.5$ remaining in the $z \geq 3$ region.

These results suggest that ground-based $UGR$ selection, while extremely successful at identifying $z \sim 3$ galaxies, may miss a significant fraction of the population. This may have a bearing on the apparent discrepancy between the surface densities of LBGs measured in the Hubble Deep Field (HDF) and in ground-based surveys. There are 12 galaxies in the HDF which have spectro-
scopic redshifts $2.8 < z < 3.5$ and $V_{606} < 25.5$ (Dickinson 1997). These galaxies correspond to those which would be detected by the “robust” LBG candidate criteria of Steidel et al. (1998). However, one would expect, given the published surface-density of “robust” LBG candidates of $\approx 0.7$ arcmin$^{-2}$ (Steidel et al. 1998), to find only three such LBGs in the HDF. Of course, cosmic variance will be significant for the HDF; but it is striking that the apparent overdensity of LBGs in the HDF corresponds with our estimate of the fraction of LBGs lost to incompleteness and confusion in the ground-based images.

4. Conclusions

We have carried out simulations to examine the effectiveness of searches for high-redshift galaxies in deep optical images typical of those obtained with 4-m telescopes. We find that the scatter of the recovered colours of model galaxies away from their model colours is two to three times greater than that expected from the photometric errors alone and arises as a result of confusion between the simulated galaxies and the real objects in the field. Because of the effects of incompleteness and confusion, the surface densities of LBGs based on ground-based imaging may be underestimated by a factor of four; this is consistent with the surface density of LBGs measured in the HDF.

To investigate these effects further, we will carry out more detailed simulations using our present data to investigate how the inferred luminosity function of the LBGs is affected by incompleteness and confusion. We also plan deep imaging programmes with the new generation of wider-field, high-image-quality instrumentation as it becomes available.

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