SCIENCE

Ultra-Deep Imaging at the William Herschel Telescope

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Ultra-deep imaging observations using powerful, ground-based telescopes such as the William Herschel Telescope (WHT) have the capacity to probe the evolutionary history of galaxies back to their formation epoch. At the faintest galaxy magnitudes, we are looking out not only in distance but back in time to when the Universe was only a few percent of its current age.

Over the past few years, we have therefore used the WHT to produce the deepest ground-based image of the sky which we have called the William Herschel Deep Field (WHDF). With exposures of ~30 hrs in U and B, the resulting images reach magnitudes which are comparable to the Hubble Deep Fields (U ~ 27, B ~ 28) but covering a five times bigger area of the sky than the two HDFs combined. As well as substantial exposures in the redder optical bands from the WHT, the field has also been imaged in the near-IR with a 30 hr exposure in K from the UKIRT IRCAM3, reaching K ~ 23 in a small central sub-area and a 14 hr exposure in H from the Calar Alto 3.5-m Omega Prime camera covering the whole 7'×7' area and reaching H ~ 23 (McCracken et al., 2000a, McCracken et al., 2000b). Table 1 summarises the current situation. Figure 1 shows an optical 'true' colour image of the WHDF.

The WHT data were taken with the Prime Focus camera using Tektronix or, more latterly, Loral CCDs. The U-band observations were much enhanced by the Loral chips, which have 3 times the sensitivity of the Tektronix at these wavelengths. Data reduction was carried out using our proprietary software (Metcalfe et al., 1991,1995).

For many aspects of the studies of high redshift galaxies, the bigger area of this Herschel Deep Field gives it a unique advantage over HST data. At intermediate redshifts ($1<z<3$) the larger numbers of galaxies means that they are more easily split into their various sub-populations by their colours. At high redshift, the big area means we have more chance of detecting candidates for galaxies in the redshift range $3<z<7$ which are within the magnitude reach of multi-object spectrographs on 8–10 m class telescopes for obtaining spectroscopic confirmation of their photometric redshift. The bigger area also has advantages for studies of high redshift galaxy clustering, aimed at understanding how structure forms in the early Universe.

Figure 2 shows the B-band galaxy counts for the WHDF compared with other data, including the Hubble Deep fields. Also shown are the predictions for a universe in which galaxies do not evolve with time, and those for which galaxies follow simple stellar population synthesis tracks (Bruzual & Charlot, 1993). Two geometries are considered, $q_0=0.05$ (open) and $q_0=0.5$ (flat). It is clear that non-evolving models underpredict the counts from quite bright magnitudes (B ~ 22). Even an open evolving model struggles to keep up with the sheer numbers of galaxies seen, although there are probably enough uncertainties in this model to 'tweak' it higher at faint magnitudes. Those who favour a closed universe have to relax the constraint that galaxy numbers are conserved (e.g. merging) or at the very least invoke a population at high redshift which has disappeared from view by the present day (e.g. fading dwarfs). The model shown is a version of the latter.

One of the main tools for scientific analysis of these data is the colour-colour diagram. It might be thought that without spectroscopy it is impossible to judge the redshifts of these faint galaxies, but Figure 3 shows this is not the case. Here, simple stellar population synthesis evolutionary tracks (Bruzual & Charlot, 1993) have been plotted for E/S0 and spiral galaxy types on top of the WHDF data. They are colour-coded by redshift. The 'hook' of galaxies toward the bottom left of the diagram is clearly identified with spirals tracking out towards redshifts of 2, whilst the prominent 'finger'

Band	Exposure (hours)	Magnitude Limit	Telescope
U	34	27	WHT
B	28	28	WHT
R	8	26.5	WHT
I	5	25.5	WHT
H	14	22.75	Calar Alto
K	1	20.5	UKIRT/Calar Alto
K sub-area	30	23	UKIRT

Table 1. Magnitude limits and exposure times for the William Herschel Deep Field.

Figure 1. A ‘true’ colour image of the William Herschel Deep Field, formed by mapping U, B and R exposures onto blue, green and red respectively. The image covers 7×7 arcminutes.

pointing upwards is composed of low redshift ellipticals. Highlighted in red are those galaxies with (R–H)>3.5. These are predicted on the basis of their optical-infrared colours to be elliptical galaxies at redshifts above ~1, in agreement with their location in Figure 3. Interestingly the scatter in (R–H) (or (R–K)) for these galaxies is very high, spanning almost 2 magnitudes.

The infra-red colours are also useful for detecting clusters of galaxies. Shown in Figure 4 are 'true' colour plots of a 1.3' box from the WHDF formed by combining R, I and H images and U, B and R images. Notice the prominent string of red galaxies to the left side on the RIH plot. This is a cluster, probably with a redshift between 0.5 and 1.

To identify high redshift galaxies the photometric 'dropout' technique (e.g. Steidel et al., 1999) is perhaps the best known. This relies on the presence of a Lyman limit in galaxy spectra, shortward of which nearly all of the flux is absorbed by intervening hydrogen. When this limit is redshifted into a particular filter the galaxy becomes very faint or disappears altogether, whilst remaining relatively bright through redder filters. Figure 5 shows three examples of such galaxies identified on the WHDF; a 'dropout' from the U-filter, implying z>3, a 'dropout' from both U and B (it is still faintly visible in B, but remember that this exposure is much deeper than the others), implying z>4, and a potential R-band 'dropout', which could have a redshift above 6 !

Using the 'dropout' technique in several bands enables us to plot the number count of galaxies at various redshift intervals. These can then be compared with simple evolutionary model predictions. Figure 6 shows such a plot for z~6 galaxies selected by R-band 'dropout' — we have included points from the Hubble Deep Fields (F606W 'dropout') and also shown the numbers of spectroscopically confirmed galaxies from surveys in the literature. We also plot the counts expected on the basis of the same simple luminosity

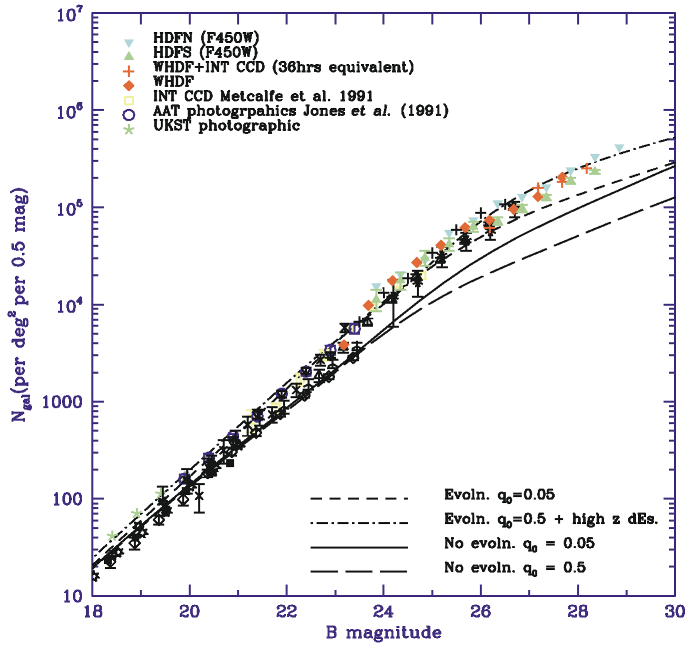

Figure 2. Differential galaxy number counts for the B-band, compared with evolving and non-evolving models for low and high q_0. Durham counts are shown with coloured symbols; b/w symbols indicate counts from the literature.

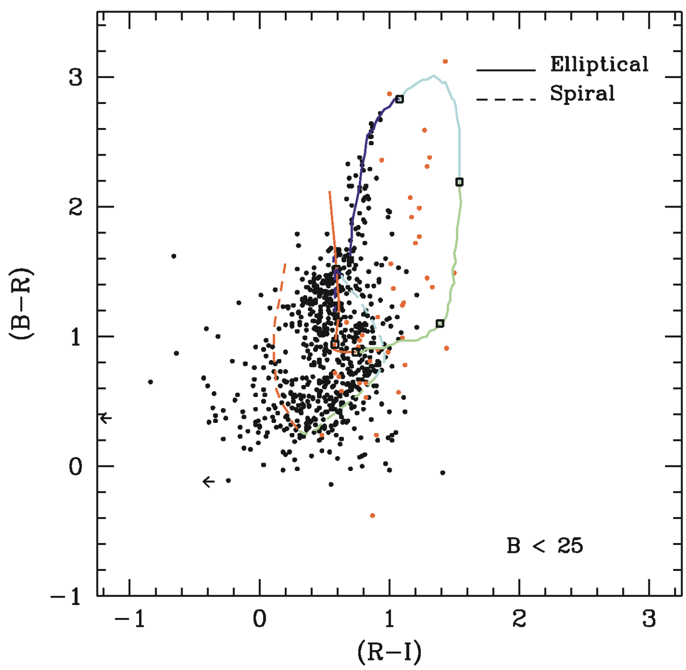

Figure 3. (B–R) versus (R–I) colour-colour plot for the WHDF, showing the predicted evolutionary tracks followed by elliptical and spiral galaxies. Colours indicate redshift range; blue z<0.5, cyan 0.5<z<1, green 1<z<2 and red 2<z<3. The red dots indicate those galaxies which are relatively bright in the infra-red ((R–H)>3.5).

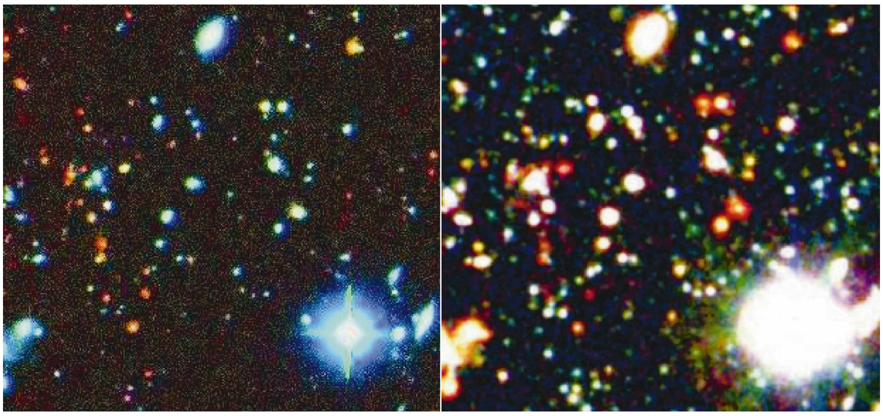

Figure 4. RIH (left) and UBR (right) 'true' colour images of a small portion of the WHDF, showing the presence of a cluster at a redshift of 0.5~1, identifiable by the presence of very red galaxies, particularly in the optical-infrared image.

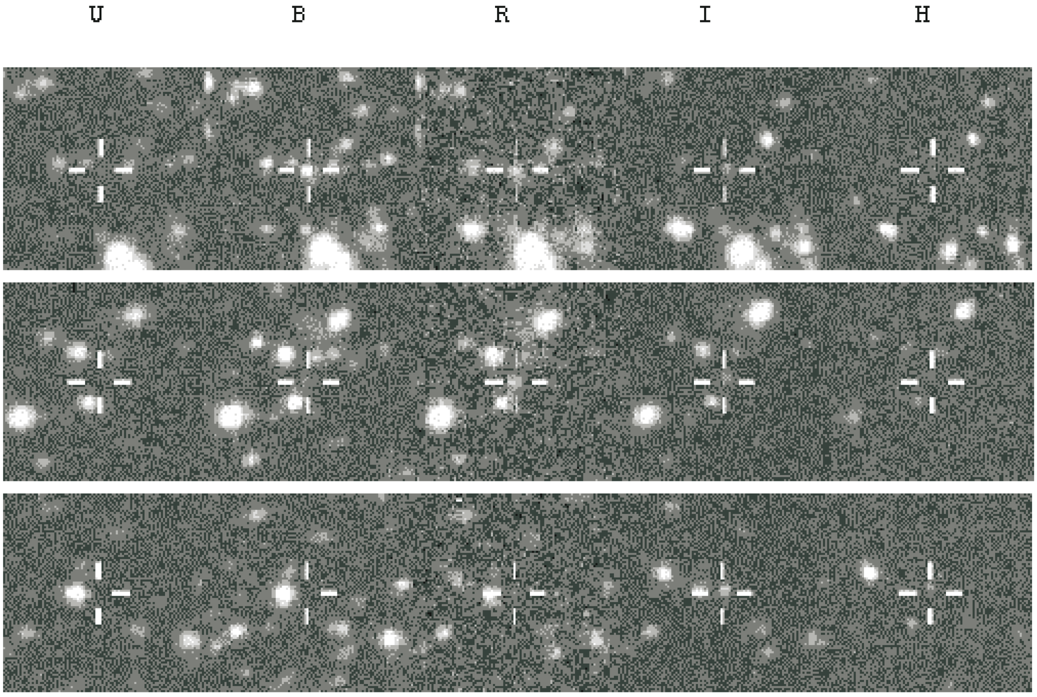

Figure 5. Top panel: An example U-dropout galaxy at B~25.0; Middle panel: A potential B-dropout galaxy with R~24.3; Bottom panel: A candidate R-dropout with I~23.8.

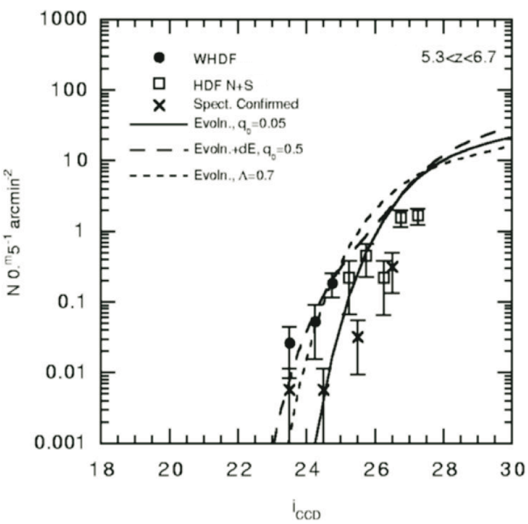

Figure 6. Numbers of R-band 'dropout' potential z~6 galaxies, together with the handful of spectroscopically confirmed such objects, compared with the predictions of simple luminosity evolution models.

evolution models as used in Figure 2. These models reproduce well our own data, and that of Steidel et al., at lower redshifts, z~3.

It is remarkable how well these simple models match this ultra-high redshift data. The fact that a population of spectroscopically confirmed z~6 galaxies have already been identified and that even larger numbers of R dropout candidates exist in both the Herschel and Hubble Deep Fields indicates that significant numbers of luminous galaxies were already extant at these redshifts, pushing the epoch of formation of giant galaxies back even earlier.

Looking to the future, we return to the WHT later this year with the aim of using the new mosaic camera to image in R, I & Z to look for R-band dropouts to fainter magnitudes and over a wider area. Such candidates will be ideal targets for the GMOS spectrograph on the new GEMINI-N 8-m telescope.

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