High-resolution imaging of faint blue galaxies

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ABSTRACT
We have used HRCam on the CFHT to obtain subarcsecond images of 26 galaxies with z=0.1–0.7 from the redshift survey of Colless et al.. The primary sample of 17 galaxies have enhanced star formation indicated by [OII] equivalent widths greater than 20Å, while the comparison sample of 9 galaxies have equivalent widths less than 10Å. By fitting exponential disks or $r^{1/4}$ bulges to B, V and I images we have derived scalelengths for the blue and red stellar populations and so established the location of the star-formation (in the nucleus or the disk) for each galaxy. We have also searched for nearby faint companions in order to determine whether the star-formation might be linked to tidal interactions or mergers. We find that these moderate-redshift galaxies generally have straightforward low-redshift analogues, in that their colours, sizes and luminosities are consistent with those of various types of z≈0 galaxies. The star-forming objects have structural components consistent with the full range of present-day disk galaxies, and absolute magnitudes spanning the range $M^*+1$ to $M^*+5$. Some of these galaxies have star-formation concentrated in their nuclei but most have star-formation occurring across the entire disk. We find companions at projected distances closer than 10 h$^{-1}$ kpc for 30% of the galaxies with enhanced star-formation, whereas none of the comparison sample have such close companions. This fraction is very similar to the 40% excess in the number of star-forming galaxies found in the redshift survey of Colless et al., and provides the first direct evidence linking interactions or mergers to the increased fraction of field galaxies with enhanced star-formation at moderate redshifts.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: starburst.

1 INTRODUCTION

At B≈22 there are approximately twice as many galaxies in the number counts as would be expected if there had been no evolution of the galaxy population. Statistically-complete redshift surveys to B=22.5 (Broadhurst et al. 1988, Colless et al. 1990, 1993) have demonstrated that the bulk of this excess comprises galaxies at modest redshifts (z<0.5) rather than luminous young star-forming galaxies at z≈2–3 as was once supposed. More recent redshift surveys (Cowie et al. 1991, Glazebrook et al. 1993) have extended this result to B=24, finding a median redshift of only z≈0.4 and few galaxies with z>1 even though the number counts exceed the no-evolution model by a factor of five at this depth.

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The large numbers and low redshifts of galaxies at faint apparent magnitudes presents a serious problem for models of galaxy evolution. Conventional models involving luminosity-independent luminosity evolution can only match the number counts with a high redshift of galaxy formation (z$_f >5$) and a low-density Universe (Ω<0.1). Even so they appear to be in conflict with the lack of objects found at redshifts z>0.5, and in particular the low redshifts found for the bluest objects with near-flat spectra (f$_{\nu}$~constant), which such models predict ought to have z>1 (Colless et al. 1993). Better matches to the observed number counts and redshift distributions are obtained by models which effectively produce density evolution of the galaxy luminosity function. Two phenomenological models that give this result invoke, respectively, a new population of star-forming dwarf galaxies that dominated the galaxy population at moderate redshifts but which have since faded beyond detection (Cowie et al. 1991, Babul & Rees 1992), or strong merging-driven evolution with a higher past star-formation...
rate which may be directly associated with the dynamical interactions (Rocca-Volmerange & Guiderdoni 1990, Broadhurst et al. 1992).

A further feature of the evolution that needs to be accounted for in any model is the increasing fraction of galaxies with large rest-frame [OII] 3727 Å equivalent widths (W_Å), indicative of enhanced star-formation. Measurements of W_Å derived from the redshift surveys of Broadhurst et al. (1988) and Colless et al. (1990, 1993), together with a more recent survey at brighter magnitudes, shows clearly that the steep slope of the galaxy counts is closely associated with the increase in the number of galaxies undergoing enhanced star-formation (see figure 2 of Broadhurst et al. 1992). Moreover, the co-added spectra of the high-W_Å galaxies suggests that the star-formation is typically strong but of relatively short (~0.1 Gyr) duration (Broadhurst et al. 1988).

What is the nature of the enhanced star-formation activity at moderate redshifts? What are the physical mechanisms that produce it? Is it triggered by galaxy interactions and/or mergers? Is it related to the formation of disks or confined to the nucleus? The current observational data (essentially counts, colours and redshifts) are not sufficient to answer these questions, since the data could, in principle, be reproduced by any process which leads to density evolution of the luminosity function. Qualitatively new information is required to determine the cause and origin of the observed evolution and decide which of the various physical processes that have been proposed actually contribute to the increased star-formation activity at moderate redshifts.

A promising approach is to take advantage of the proximity of those star-forming galaxies that represent the count excess and use the best ground-based images with seeing FWHM~0.5 arcsec to resolve details on scales of ~2 h^{-1} kpc (H_0=100h km s^{-1} Mpc^{-1}). Sufficiently deep high-resolution images can therefore provide independent measures of surface brightness at many points across the face of moderate-redshift galaxies. By imaging in two colours the light distributions for the star-forming (blue) component and the quiescent stellar distribution (as revealed in the near infrared) can be compared to establish whether the star formation is localised in the nucleus or disk or uniformly distributed across the entire galaxy, and whether it is triggered by tidal interactions (signalled by distorted isophotes and/or close companions).

An initial step in this direction was taken by Giraud (1992) who observed 30 faint (22<V<24.5), flat-spectrum (V−I<0.8), low surface brightness (μ_V>23) galaxies. Using the NTT he obtained V and I images with seeing FWHM better than 0.85 arcsec in V and 0.7 arcsec in I. The galaxies (whose redshifts are not known) were found to fall into three broad classes: compact (having a dominant point source and fainter envelope), irregular (elongated, spiral or distorted) and multiple (more than one peak in surface brightness). The relative numbers of objects in these classes were approximately 2:3:1.

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**Table 1. Sample of galaxies.**

| ID | R.A. (1950) | Dec. | b_J | b_J−r_F | z   | W_Å(Å) | M_{b_J} | V (A,B,C) |
|----|-------------|------|-----|---------|-----|--------|---------|----------|
| 10.2.05 | 10 44 02.86 | +00 00 58.5 | 21.72 | 1.91 | 0.303 | 4 | −19.2 | 20.7 |
| 10.2.17 | 10 44 04.53 | +00 00 18.3 | 21.75 | 1.26 | 0.302 | 37 | −18.6 | 21.1 |
| 10.2.23 | 10 44 04.00 | +00 01 53.1 | 22.36 | 1.29 | 0.665 | 75 | −20.1 | 22.9,23.8,24.0 |
| 13.2.10 | 13 42 04.80 | +00 11 09.9 | 21.71 | --- | 0.424 | 0 | −20.8 | 21.1 |
| 13.2.13 | 13 42 05.53 | +00 10 26.5 | 21.82 | 1.92 | 0.430 | 23 | −20.0 | 21.7,24.0 |
| 13.2.22 | 13 42 06.40 | +00 12 04.5 | 22.19 | 1.25 | 0.422 | 29 | −19.0 | 21.8 |
| 13.4.12 | 13 41 13.65 | +00 02 21.5 | 21.50 | --- | 0.120 | 38 | −16.8 | 20.8 |
| 13.4.16 | 13 41 13.68 | +00 00 31.2 | 21.72 | 0.95 | 0.120 | 56 | −16.3 | 21.3 |
| 13.4.22 | 13 41 15.73 | +00 00 51.9 | 22.10 | 0.67 | 0.086 | 36 | −15.1 | 21.8 |
| 13.5.06 | 13 41 12.78 | +00 08 06.0 | 22.40 | 1.25 | 0.112 | 54 | −15.5 | 22.0,24.4 |
| 13.5.07 | 13 41 13.60 | +00 08 29.5 | 21.32 | 0.56 | 0.220 | 24 | −17.7 | 21.3 |
| 13.5.10 | 13 41 06.50 | +00 12 19.8 | 21.57 | 1.45 | 0.329 | 31 | −19.1 | 20.8 |
| 13.5.12 | 13 41 13.13 | +00 11 45.5 | 21.63 | 1.19 | 0.678 | 27 | −20.8 | 21.5 |
| 13.5.14 | 13 41 08.95 | +00 12 52.5 | 21.83 | --- | 0.255 | 29 | −18.8 | 21.1 |
| 13.5.20 | 13 41 06.72 | +00 09 01.8 | 22.30 | 1.75 | 0.521 | 25 | −19.9 | 21.6 |

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| (b) 1993 April 20–22 |
| ID | R.A. (1950) | Dec. | b_J | b_J−r_F | z   | W_Å(Å) | M_{b_J} | B (A,B,C) |
|----|-------------|------|-----|---------|-----|--------|---------|----------|
| 10.2.02 | 10 43 48.77 | +00 07 38.6 | 21.40 | 0.73 | 0.549 | 8 | −19.4 | 21.2 |
| 10.2.04 | 10 43 55.81 | +00 08 50.6 | 21.71 | 0.58 | 0.543 | 0 | −19.1 | 21.8 |
| 10.2.11 | 10 44 01.25 | +00 09 41.5 | 21.63 | 1.24 | 0.277 | 27 | −19.1 | 21.6,22.6 |
| 10.2.15 | 10 43 49.40 | +00 08 11.9 | 21.70 | 1.77 | 0.451 | 8 | −20.1 | 22.3 |
| 10.2.20 | 10 43 45.16 | +00 07 16.6 | 22.02 | 1.79 | 0.188 | 0 | −17.5 | 22.1 |
| 10.2.22 | 10 43 49.11 | +00 11 09.3 | 22.11 | 0.89 | 0.180 | 31 | −16.8 | 22.0 |
| 10.2.25 | 10 43 48.10 | +00 06 38.0 | 22.43 | 0.90 | 0.160 | 20 | −16.2 | 22.6 |
| 13.2.17 | 13 41 52.15 | +00 03 07.1 | 22.08 | 1.42 | 0.202 | 0 | −17.4 | 22.5 |
| 13.2.23 | 13 41 59.64 | +00 05 42.9 | 22.33 | 1.49 | 0.281 | 0 | −18.1 | 22.8 |
| 13.2.26 | 13 41 54.18 | +00 03 26.0 | 22.41 | 0.64 | 0.598 | 8 | −18.6 | 22.5 |
| 13.2.36 | 13 41 58.30 | +00 04 46.9 | 22.75 | 1.51 | 0.537 | 32 | −19.4 | 22.9 |

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This paper reports the results of a programme of high-resolution multicolour imaging of star-forming galaxies with measured redshifts and [OII] equivalent widths from the survey of Colless et al. (1990, 1993). Section 2 describes the selection of the target galaxies and the observations. Section 3 outlines the method used to obtain scalelengths for the galaxies and gives a detailed description of each object. The galaxies’ morphologies, their size–luminosity relation and the incidence of close companions are discussed in Section 4 in relation to evolutionary models. Our conclusions are presented in Section 5.

2 OBSERVATIONS

The galaxies selected for imaging were taken from the deep redshift survey of Colless et al. (1990, 1993). They fall into two classes: a primary sample of 17 galaxies with [OII] 3727Å equivalent widths $W_{\lambda}>20$Å, indicative of enhanced star-formation, and a comparison sample of 9 galaxies with $W_{\lambda}<10$Å. Details of the galaxies observed are given in Table 1, which lists identification number from the redshift survey, R.A. and Dec. (1950), $b_j$ magnitude, $b_j-r_F$ colour, redshift, [OII] 3727Å $W_{\lambda}$, and approximate absolute $b_j$ magnitude. Fig. 1 displays the distributions of apparent magnitude, absolute magnitude and $W_{\lambda}$ for the galaxies imaged in this study, and shows that they are statistically representative of the galaxies in the redshift survey.

Table 2. Log of observations.

| Field | Objects | I    | V1  | V2  |
|-------|---------|------|-----|-----|
| (a) 1992 April 7–8 |
| 10F1  | 10.2.05 | 1800s| 2700s | 2700s |
| 10.2.17 | 0.56") | 0.69") | 0.72") |
| 10.2.23 | | | |
| 13F1  | 13.4.12 | 1800s| 3000s | 1800s |
| 13.4.16 | 0.59") | 0.91") | 0.55") |
| 13.4.22 | | | |
| 13F2  | 13.5.06 | 1800s| 1300s | 3600s |
| 13.5.07 | 0.59") | 0.55") | 0.57") |
| 13.5.20 | | | |
| 13F3  | 13.5.10 | 1800s| 5400s | |
| 13.5.12 | 0.62") | 0.70") | |
| 13.5.14 | | | |
| 13F5  | 13.2.10 | 1800s| 5400s | |
| 13.2.13 | 1.21") | 1.01") | |
| 13.2.22 | | | |

| (b) 1993 April 20–22 |
| Field | Objects | B1  | B2  | I1  | I2  |
|-------|---------|-----|-----|-----|-----|
| 10F2  | 10.2.02 | 5000s| 5000s | 2000s | 2000s |
| 10.2.15 | 1.00") | 0.80") | 0.90") | 0.60") |
| 10.2.20 | | | | |
| 10.2.25 | | | | |
| 10F3  | 10.2.04 | 5000s| 2000s | |
| 10.2.11 | 1.00") | 0.70") | |
| 10.2.22 | | | | |
| 13F4  | 13.2.17 | 5000s| 2000s | |
| 13.2.26 | 0.80") | 0.80") | |
| 13F7  | 13.2.23 | 5000")| 2000s | |
| 13.2.36 | 1.50") | 1.00") | |

The observations were made with HRCam on the Canada-France-Hawaii Telescope (CFHT) during the nights of 1992 April 7–8 and 1993 April 20–22. HRCam is a high-resolution camera which can fast-guide at 10–200 Hz using a bright nearby guide star in order to achieve improved image quality over a 2.2 arcmin diameter field. A detailed description is given by McClure et al. (1989). During the first run we used the SAIC1 1024×1024 CCD, which had a pixel size of 0.13 arcsec. The I filter used had $\lambda_c=8310$Å and $\Delta\lambda=1970$Å; the V filter used had $\lambda_c=5420$Å and $\Delta\lambda=900$Å (we were obliged to use V rather than B due to this CCD’s poor blue response). For the second run we were able to image in B and I using the Loral 3 2048×2 CCD, which has 0.11 arcsec pixels. The B filter used in this run had $\lambda_c=4300$Å and $\Delta\lambda=970$Å, while the I filter was the same as for the previous run.

All the observations are summarised in Table 2, which gives, for each field, the targets in that field and the total integration time and seeing FWHM for the images in each filter. Where there were two series of exposures with slightly different pointings or seeing they were co-added separately. The seeing point spread functions (PSFs) were measured from a few stars on each image. All fields from the first run have I and V images with effective seeing FWHM of 0.5–0.7 arcsec, with the exception of 13F5 which has FWHM of 1.0 arcsec in V and 1.2 arcsec in I. The fields from the second run have B and I images with FWHM of 0.6–1.0 arcsec, with the exception of the B image of 13F7, which has a FWHM of 1.5 arcsec.

Although these images were not taken in photometric
conditions we have approximately zero-pointed the B and V magnitudes by one-to-one comparison of the objects on each image with the $b_J$ and $r_F$ photometry from Colless et al. (based on Jones et al. 1991). The B and V magnitudes thus derived are given in Table 1 for each of the resolved objects close to the position of the target galaxy. These magnitudes have an rms error of 0.2 mag.

Fig. 2 shows the V and I or B and I images in a small region about each target galaxy. The seeing FWHM is shown as the small vertical bar on each image (see also Table 2), while the larger horizontal bar on the leftmost image corresponds to 5 h$^{-1}$ kpc at the redshift of the galaxy. In the cases where there is more than one resolved object close to the position of the target galaxy, these are labelled A, B, C in decreasing order of brightness.

Five of the objects in the sample (10.2.11, 10.2.23, 13.2.13, 13.5.06 and 13.5.07) are seen in Fig. 2 to have close companions. The closer pairs were not resolved in the $b_J$ and $r_F$ photometry (based on prime focus AAT plates taken in 1.5–2.5 arcsec seeing), so that the $b_J$ and $r_F$ magnitudes for these objects in Table 1 refer to the pair combined. The B and V magnitudes in Table 1, however, are for each object individually, and in general there is a magnitude or more difference between objects A and B. We may therefore reasonably attribute the spectroscopically-measured parameters (redshifts and equivalent widths) to the brighter object. The exception is 13.5.07, where the objects are still only partially resolved in 0.6 arcsec seeing, and also appear more similar in magnitude; only a combined V magnitude is given in Table 1.

3 ANALYSIS

The resolution of the images in Fig. 2 is insufficient to permit a direct visual classification of the galaxies’ morphologies. We can still obtain useful information, however, from the overall form and extent of their light profiles. Although we cannot achieve a full bulge/disk decomposition, we can say whether individual objects are best fit by exponential disks, $r^{1/4}$-law bulges or as point sources. We can also establish a scalelength for each galaxy and obtain a size-luminosity relation. Finally, by comparing the scalelengths obtained in our two colours, we may obtain an indication of the relative importance of the bulge and disk in each object.

In order to carry out this analysis, we have fitted two-dimensional exponential disks and $r^{1/4}$ bulges directly to the images of Fig. 2 using $\chi^2$-minimisation. Because seeing effects are significant, before fitting we have convolved the models with a stellar profile either taken from the same frame or from a frame with very similar seeing FWHM. In the case of close pairs of objects only the brighter was fitted, with the companion’s image excised. Fig. 3 compares the surface brightness profiles (in circular apertures) of the galaxies and the best-fitting models. The B and V surface brightness scales in the figure are based on the calibration described in Section 2; the I calibration is only approximate. The models generally fit the profiles within the errors down to a surface brightness in B and V of $\mu \approx 25–26$ mag arcsec$^{-2} \approx 29.5–30.5$ mag pixel$^{-2}$. These limits typically correspond to between three and five times the galaxy’s scalelength. The results of the fits are presented in Table 3, which lists the parameters of the best-fitting models: the disk scalelength in both arcsec and h$^{-1}$ kpc (or effective radius where a bulge fitted significantly better, indicated in the table by an asterisk), and the axial ratio.

In order to check the results of the fitting procedure we simulated galaxy images bracketing the range of S/N and structural parameters observed in our data. We constructed sets of model disk galaxies with scalelengths ranging from 0.05 arcsec for the smallest set up to 1.0 arcsec for the largest, and sets of model bulges with effective radii from 0.45 arcsec to 2.5 arcsec. Each set consisted of 36 models. The total counts in the model galaxies were matched to those of the observed galaxies. The models were placed at random locations with respect to pixel centres, and we convolved them with stellar profiles from our data which spanned the range in seeing of our observations. Finally we added sky and Poisson noise.

These simulated images were then analysed in the same way as the data. We measured the galaxy centroids and the sky levels from the images (rather than fixing them at their known values), then applied our fitting procedure. The fitted parameters for each set of 36 models were then compared to the input parameters to estimate the distribution of errors. We found that these distributions were approximately normal, and that the errors given by the fitting routine were reliable in that on average approximately 68% of the true values were within the estimated error of the fitted value and approximately 95% were within twice the estimated error. We also found that, over the range of seeing in our observations, the errors in the scale sizes increased only slowly with increasing FWHM.

These simulations, which mimic as closely as possible the properties of the galaxies and noise in our data, thus give us confidence in the errors we estimate for the fitted parameters. As Table 3 shows, these errors are generally small compared to the galaxies’ scalelengths. We conclude that the depth and spatial resolution of our images are sufficient to derive reliable scalelengths for all but the smallest of our target galaxies.

As well as fitting simulated disk galaxies with disk models and simulated bulge galaxies with bulge models, we also fitted disks with bulges and bulges with disks, since for real galaxy images we have no way of knowing in advance the appropriate model to fit. We found that, for the range of scale sizes, S/N and seeing FWHM in our observations, the discrimination between a disk galaxy and a bulge galaxy was considerably better in those cases where the ratio of FWHM to scale size was smaller. This improved ability to discriminate disks and bulges was the main benefit derived from the reduction in the seeing FWHM produced by HRCam’s fast guiding. Although our data are not adequate for quantitative measurement of bulge-to-disk ratios, in most cases they are adequate to discriminate between bulge-dominated galaxies and disk-dominated galaxies.

In fact most of the galaxies in the sample can be adequately fit by an exponential disk. Only two galaxies (10.2.15 and 10.2.20) were significantly better fit by an $r^{1/4}$ bulge, while seven objects could not be satisfactorily fitted because they were either unresolved or only marginally resolved. In the latter case the objects could be equally well fitted by a disk or a bulge because the light distribution, though extended, was still dominated by the seeing PSF. Only upper
Figure 2. (a) V and I images in a region 7.9 arcsec (61 pixels) square about each target galaxy from the 1992 observations. The I image is at left, with the V1 and V2 images to the right. The seeing FWHM is shown as the small vertical bar on each image; the horizontal bar on the I image corresponds to 5 h$^{-1}$ kpc at the redshift of the galaxy.
Figure 3. *

(b) B and I images in a region 6.7 arcsec (61 pixels) square about each target galaxy from the 1993 observations. The B1 and B2 images are at left, with the I1 and I2 images to the right. The seeing FWHM is shown as the small vertical bar on each image; the horizontal bar on the B1 image corresponds to $5 \, h^{-1} \, \text{kpc}$ at the redshift of the galaxy.
Figure 4. (a) Surface brightness profiles in circular apertures for each target galaxy from the 1992 observations (points with error bars), together with the best-fitting model including seeing convolution (dotted lines).
Figure 5. *
(a) – continued
Figure 6. *

(b) Surface brightness profiles in circular apertures for each target galaxy from the 1993 observations (points with error bars), together with the best-fitting model including seeing convolution (dotted lines). Note that there is no plot for 10.2.11 I1 because the galaxy was too near the edge of the frame (see Fig 2b).
Figure 7. *
(b) – continued
Table 3. Disk scalelengths and axial ratios.

| Galaxy image | Scalelength (arcsec) | Axial ratio | Galaxy image | Scalelength (arcsec) | Axial ratio |
|--------------|----------------------|-------------|--------------|----------------------|-------------|
| 10.2.05 I    | <0.05                | —           | 10.2.02 I    | <0.05                | —           |
| V1           | <0.05                | —           | V2           | <0.05                | —           |
| 10.2.17 I    | 0.37 (0.02)          | 1.02 (0.06) | B1           | <0.05                | —           |
| V1           | 0.34 (0.01)          | 0.94 (0.03) | B2           | <0.05                | —           |
| V2           | 0.38 (0.01)          | 1.05 (0.03) | B1           | <0.2                 | <0.7        |
| 10.2.23 I    | <0.2                 | <0.8        |              |                      |             |
| V1           | <0.2                 | <0.8        | B1           | 0.74 (0.06)          | 1.94 (0.16) |
| 13.2.10 I    | 0.45 (0.01)          | 1.49 (0.03) | 10.2.15 I    | 1.28 (0.11)*         | 4.35 (0.37)*|
| V1           | 0.40 (0.02)          | 1.32 (0.07) | I2           | 1.05 (0.04)*         | 3.57 (0.14)*|
| 13.2.13 I    | 0.85 (0.12)          | 2.83 (0.40) | B1           | 0.53 (0.09)*         | 1.80 (0.31)*|
| V1           | 0.36 (0.02)          | 1.20 (0.07) | B2           | 0.61 (0.04)*         | 2.08 (0.14)*|
| 13.2.22 I    | 0.38 (0.08)          | 1.26 (0.26) | 10.2.20 I    | 1.12 (0.32)*         | 2.26 (0.65)*|
| V1           | 0.59 (0.05)          | 1.95 (0.17) | I2           | 0.96 (0.06)*         | 1.94 (0.12)*|
| 13.4.12 I    | 0.19 (0.06)          | 0.27 (0.09) | B1           | 0.74 (0.18)*         | 1.50 (0.36)*|
| V1           | 0.22 (0.02)          | 0.31 (0.03) | B2           | 0.37 (0.09)*         | 0.75 (0.18)*|
| 13.4.16 I    | 0.59 (0.03)          | 0.84 (0.04) | 10.2.22 I    | 0.47 (0.02)          | 0.92 (0.04) |
| V1           | 0.67 (0.04)          | 0.96 (0.06) | B1           | 0.50 (0.01)          | 0.98 (0.02) |
| V2           | 0.71 (0.04)          | 1.01 (0.06) | B2           | 0.57 (0.12)          | 1.02 (0.22) |
| 13.4.22 I    | 0.50 (0.03)          | 0.54 (0.03) | 10.2.25 I    | 0.74 (0.10)          | 1.32 (0.18) |
| V1           | 0.48 (0.04)          | 0.52 (0.04) | I2           | 0.96 (0.06)*         | 1.94 (0.12)*|
| V2           | 0.48 (0.03)          | 0.52 (0.03) | B2           | 0.63 (0.04)          | 1.08 (0.07) |
| 13.5.06 I    | <0.05                | —           | 10.2.17 I    | <0.05                | —           |
| V1           | <0.05                | —           | V2           | <0.05                | —           |
| 13.5.07 I    | 0.32 (0.02)          | 0.72 (0.05) | B1           | <0.1                 | —           |
| V1           | 0.35 (0.02)          | 0.79 (0.05) | 13.2.10 I    | 0.41 (0.04)          | 1.08 (0.11) |
| V2           | 0.35 (0.01)          | 0.79 (0.03) | 13.2.23 I    | 0.47 (0.11)          | 1.24 (0.29) |
| 13.5.10 I    | 0.71 (0.03)          | 2.06 (0.09) | B1           | <0.1                 | —           |
| V1           | 0.92 (0.03)          | 2.67 (0.09) | 13.3.26 I    | 0.17 (0.07)          | 0.62 (0.26) |
| 13.5.12 I    | 0.77 (0.06)          | 3.03 (0.24) | B1           | 0.50 (0.12)          | 1.83 (0.14) |
| V1           | 1.54 (0.13)          | 6.06 (0.51) | 13.5.14 I    | 0.53 (0.04)          | 1.32 (0.10) |
| V2           | 0.83 (0.03)          | 2.06 (0.07) | V2           | 0.83 (0.03)          | 0.73 (0.03) |
| 13.5.20 I    | 0.45 (0.03)          | 1.63 (0.11) | B1           | 0.50 (0.12)          | 1.83 (0.14) |
| V1           | 0.59 (0.06)          | 2.14 (0.22) | V2           | 0.62 (0.04)          | 2.25 (0.14) |
| V2           | 0.62 (0.04)          | 2.85 (0.08) | —             |                      |             |

limits to the scalelengths of these seven objects are given in Table 3, and these limits are also uncertain. They include 5 of the 9 low-\(W_\lambda\) objects and just 2 of the 17 high-\(W_\lambda\) objects (10.2.23 and 13.5.06), both of which have close companions and very large \(W_\lambda\). There is excellent agreement between the fitted parameters obtained from repeat images in the same passband, and a correlation between the V and I or B and I scalelengths, with the blue scalelengths tending to be larger than the red.

In Fig. 4 the scalelengths of the sample galaxies, as measured from both the blue and red images, are plotted against their absolute \(b_J\) magnitudes. For comparison, the same diagram is plotted for a sample of low-redshift galaxies with V and I scalelengths measured by Ryder (1993) from CCD surface photometry and absolute B magnitudes from the Nearby Galaxies Catalogue (Tully 1988; converted to \(h=1\) kpc). There is excellent agreement between the fitted parameters obtained from repeat images in the same passband, and a correlation between the V and I or B and I scalelengths, with the blue scalelengths tending to be larger than the red.

4 DESCRIPTIONS OF INDIVIDUAL OBJECTS

Combining the redshifts, equivalent widths, colours and absolute magnitudes from the Colless et al. redshift survey with the new imaging data, we describe in this section the morphological type and mode of star formation for each of the 26 galaxies in the sample. The main results and trends drawn from this detailed analysis are discussed in the following section.

10.2.05: This M_{b_J} = -19.2 object has a low [OII] equivalent width (\(W_\lambda = 4\AA\)) and a colour of \(b_J - r_F = 1.91\), consistent with an elliptical at its redshift of \(z = 0.303\) (see, e.g., figure 12 of Colless et al. 1990). However it appears to be unusually compact, since an elliptical galaxy of this absolute magnitude would typically have an effective radius of \(\sim 2.5 \, h^{-1}\) kpc (see, e.g., figure 4 of Sandage & Perelmuter 1990) and should appear extended, whereas this object is unresolved. It unresolved nature and colour might also be consistent with a late-type star, however its spectrum is unambiguously that of an early-type galaxy at \(z = 0.303\).

10.2.17: At the same redshift as 10.2.05, this M_{b_J} = -18.6 object is well-fit by an exponential disk with
intrinsically brightest objects in the sample at $M_b = -20.8$ (i.e. $\sim$1 mag brighter than $M^*$) and is probably a giant early-type spiral or S0.

13.2.13: The main object (A in Fig. 2) has a much redder companion (B) at a projected separation of 6.3 h$^{-1}$ kpc. As with 10.2.23, the two objects were not resolved in the photographic photometry, however B, though prominent in I, is 2.3 mag fainter than A in V. The measured absolute magnitude of $M_b = -20.0$ is thus not likely to be much altered, although the red $b_J - r_F$ colour is due to the very red companion. The disk scalelength fitted in I is over twice that found in V, probably because of inadequate removal of contaminating light from the companion. The V estimate of 1.2 h$^{-1}$ kpc is therefore preferred. The galaxy appears to be an M$^*$ spiral with moderate star-formation ($W_{\lambda}=23\AA$) over its whole disk. It is possible the star-formation is related to the presence of a close companion, but if so the burst is mild and global, similar to 10.2.11 and unlike 10.2.23 or 13.5.06 where the evidence links the close companions to strong star-formation within a small region, probably just the nucleus.

13.2.22: This object, at a similar redshift (z=0.422) to both 13.2.10 and 13.2.13, has $W_{\lambda}=29\AA$. The V scalelength is 50% greater than that in I, implying that the old stellar population in this sub-L$^*$ galaxy is more concentrated than the star-forming regions. Together with a colour of $b_J - r_F = 1.25$, this suggests the galaxy is a mid- to late-type spiral with moderate star-formation in the disk.

13.4.12: Like 10.2.23, this object, though clearly extended, does not yield very reliable fits, mainly because it is very flat (axial ratio $\sim$0.1). At z=0.120 it is one of the closer objects in the sample, so that the scalelength of 0.2 arcsec corresponds to just 0.3 h$^{-1}$ kpc. Even though it is a relatively faint galaxy ($M_b = -16.8$), this scalelength puts it well below the mean relation in Fig. 4. The data are consistent with an edge-on spiral galaxy undergoing a strong burst of star-formation ($W_{\lambda}=38\AA$). This star-formation is unlikely to be concentrated in the nucleus, as the object would then appear round rather than flat.

13.4.16: This object provides an interesting contrast to 13.4.12. Although at the same redshift and with a similarly high [OII] equivalent width ($W_{\lambda}=56\AA$) and faint absolute magnitude ($M_b = -16.8$), it has a V disk scalelength of 1 h$^{-1}$ kpc, larger than might be expected for such a faint galaxy (see Fig. 4). Comparison of the V and I images shows that the blue and red stellar populations are co-extensive and that the strong star-formation indicated by $W_{\lambda}$ and the colour of $b_J - r_F = 0.95$ is occurring over the whole disk of what is probably a late-type spiral.

13.4.22: At z=0.086 this is the lowest redshift object in the sample and has the faintest absolute magnitude ($M_b = -15.1$). It also has the most irregular isophotes, although both the V and I images are well-fit by an exponential disk of scalelength 0.5 h$^{-1}$ kpc. This puts it slightly above the extrapolated ridge-line of the size-luminosity relation (see Fig. 4). It has $W_{\lambda}=36\AA$ and $b_J - r_F = 0.67$, and is probably a star-forming irregular galaxy.

13.5.06: This object is similar to 13.4.22, having z=0.112, $M_b = -15.5$ and $W_{\lambda}=54\AA$. However it has a much redder companion at a projected separation of just 1.9 h$^{-1}$ kpc which was not resolved in the photographic image, explaining the colour of $b_J - r_F = 1.25$. The main object...
(A in Fig. 2) is unresolved even in the HRCam images, so that it is a good candidate for a strong burst of (possibly nuclear) star-formation in a dwarf galaxy, which may have been triggered by the close companion.

13.5.07: This object is in fact a very close pair of galaxies (separation 1.7 h⁻¹ kpc) that are only just resolved in the HRCam images. The pair overlap too much to permit separate photometry of the components, and in fact it is possible to fit an exponential disk (scalelength 0.8 h⁻¹ kpc) to the combined system, although the fits to some of the images are poor and the axial ratio is just 0.2. At z=0.220, the pair have a combined luminosity of M_b = −17.7. The colour of the combined system is very blue (b−r_F=1.56) but the [OII] emission (W_A=24Å) is relatively weak. If tidal interactions are causing the star formation, then this system more closely resembles 13.2.13 than the probable nuclear starbursts in 10.2.23 and 13.5.06.

13.5.10: With z=0.329 and M_b = −19.1, this galaxy is similar to 10.2.17. It has a red colour (b−r_F=1.45) for its [OII] equivalent width of 31Å, and is not well fit by an exponential disk. The data are consistent with an early-type spiral having a significant bulge component and star-formation occurring in its disk.

13.5.12: At z=0.678 this is the most distant object in the sample. It is also the biggest and (with 13.2.10) the brightest, having M_b = −20.8. The V image is well-fit by a disk with a scalelength of 6 h⁻¹ kpc, however the I image is not so well fit, due to a more significant bulge, and has a scalelength of just 3 h⁻¹ kpc. The colour of b−r_F=1.19 and equivalent width of W_A=27Å suggest moderate star-formation is occurring over a very extended disk in an unusually bright mid-type spiral.

13.5.14: As with 13.5.12, this galaxy has a larger V than I scalelength (2 h⁻¹ kpc compared to 1.3 h⁻¹ kpc) and is not as well fitted by a disk in I. It has M_b = −18.8 and, with an [OII] equivalent width of 29Å, appears to be a mid-type spiral with moderate star-formation across occurring its disk.

13.5.20: This object at z=0.521 has quite a red colour (b−r_F=1.75) but an equivalent width of 25Å. It is well-fit in both V and I by a pure disk with only a 30% greater scalelength in V than I. It has a luminosity close to L*, and is probably an early-type spiral with star-formation in its disk.

10.2.02: This object has a redshift of z=0.549 and an absolute magnitude of M_b = −19.4. It is very compact in both the B and I images, being essentially unresolved. Given its very blue colour (b−r_F=0.73), it has a low [OII] equivalent width (W_A=8Å).

10.2.04: Also unresolved in both B and I, this object has similar redshift (z=0.543), absolute magnitude (M_b = −19.1) and colour (b−r_F=0.58) to 10.2.02, although it has no detected [OII].

10.2.11: This object at z=0.277 has a companion one magnitude fainter in B at a projected distance of 5 h⁻¹ kpc. The two objects are clearly resolved although their isophotes overlap. The brighter (A in Fig. 2) is adequately represented by a disk of scalelength 1.9 h⁻¹ kpc in B. Unfortunately the object fell at the very edge of the I frame and so the red scalelength could not be obtained. The combined absolute magnitude and colour of the pair are M_b = −19.1 and b−r_F=1.24. The [OII] equivalent width of W_A=27Å and the smooth distribution of blue light across the disks of both objects imply that if the star-formation is related to interaction between the pair, it is relatively mild and global (similar to 13.2.13) rather than a strong nuclear burst (as in 10.2.23 and 13.5.06).

10.2.15: This object is marginally better fit by an r¹/₄ bulge than an exponential disk in both B and I. Subtracting the best-fit bulge leaves a faint indication of extended structure. The image appears to be that of a M° bulge-dominated spiral, which is consistent with the observed colour of b−r_F=1.77 (for the object’s redshift of z=0.451) and its low [OIII] equivalent width (W_A=8Å).

10.2.20: As with 10.2.15, this object is better fit by a bulge than a disk in both B and I. There is faint residual structure that might be an edge-on disk. Again, the colour (b−r_F=1.79) is consistent with a bulge-dominated spiral at the object’s redshift of z=0.188. However the absolute magnitude (M_b = −17.5) is considerably fainter than that of 10.2.15. No [OII] emission is detected in this galaxy.

10.2.22: At a redshift of z=0.180, this galaxy has M_b = −16.8 and b−r_F=0.89. The blue colour accords with its strong [OII] emission (W_A=31Å). It is fit in both B and I by a disk with scalelength 0.9 h⁻¹ kpc, and is of roughly typical size for its luminosity (Fig. 4). This object appears to be a strongly star-forming late-type dwarf galaxy.

10.2.25: This object is very similar to 10.2.22, though somewhat fainter at M_b = −16.2. It has z=0.160 and b−r_F=0.90, and an [OII] equivalent width of W_A=20Å. It is slightly larger than 10.2.22, with a B and I scalelength of 1.0 h⁻¹ kpc, making it somewhat larger than usual given its fainter luminosity. It too appears to be a late-type dwarf galaxy with enhanced star-formation.

13.2.17: This object is effectively unresolved in both B and I. It has a redshift of z=0.202 and an absolute magnitude of M_b = −17.4. Its colour is b−r_F=1.42 which corresponds to a bulge-dominated spiral at this redshift. No [OII] emission is detected.

13.2.23: Although it has a similar redshift (z=0.281) and colour (b−r_F=1.49) to 13.2.17, and also has no [OII], this object is nearly a magnitude brighter, at M_b = −18.1. It is also well-fit in both B and I by an exponential disk of scalelength 1.1−1.2 h⁻¹ kpc, exactly as expected for a galaxy of this luminosity, and is in all respects consistent with being an early-type spiral.

13.2.26: This high-redshift (z=0.598) galaxy is similar to 10.2.02, having M_b = −18.6, a low [OII] equivalent width (W_A=8Å) and a very blue colour (b−r_F=0.64). It is also unresolved, although both the B and I images of this object were taken in relatively poor (1−1.5 arcsec) seeing.

13.2.36: This object has z=0.537, M_b = −19.4 and b−r_F=1.54. It is well-fit in B by a disk of scalelength 1.8 h⁻¹ kpc, consistent with its luminosity, but in I by a disk of scalelength 0.6 h⁻¹ kpc. The colour, large [OII] equivalent width (W_A=32Å), and the larger blue than red scalelength suggest that this was a relatively small faint galaxy that has been brightened by strong star-formation over the whole of an extensive disk. It is thus similar to 13.5.12.
5 DISCUSSION

There is considerable morphological variation amongst the objects in both the high-$W_\lambda$ and low-$W_\lambda$ samples. A visual impression of this morphological variety can be obtained by comparing in Fig. 2 the objects with similar redshifts, such as 13.4.12 and 13.4.16 (both $z=0.120$), 10.2.05 and 10.2.17 ($z=0.303,0.302$), and 10.2.23 and 13.5.12 ($z=0.665,0.678$).

Comparison of the blue and red images does not in general show significant variations in colour across the face of individual galaxies on small scales (comparable to the seeing disk, i.e. 1–2 h$^{-1}$ kpc), although to be detectable the variation in colour would have to be of the order of 0.5 mag on these scales. Most (15/17) of the high-$W_\lambda$ objects apparently have star-formation occurring globally, indicated both by the relatively smooth distribution of the blue light and by a blue scalelength comparable to or larger than the red scalelength. Only two objects (10.2.23 and 13.5.06) show evidence for nuclear starbursts. The former is the second most distant object in the sample, at $z=0.665$, while the latter is one of the closer objects, at $z=0.112$. Both objects have very large [OII] equivalent widths and close companions, and are particularly strong cases for interaction-triggered star-formation. Other objects with similarly large $W_\lambda$ (e.g. 10.2.17 and 13.4.16) do not have close companions, while the remaining three galaxies with close companions (13.2.13, 13.5.07 and 10.2.11) have $W_\lambda=20$–$30$ A and show apparently global star-formation.

The scalelengths of the extended objects vary from 0.3 h$^{-1}$ kpc for the compact 13.4.12 ($W_\lambda=38$ A) at $z=0.120$, to 6 h$^{-1}$ kpc for 13.5.12 ($W_\lambda=27$ A), which at $z=0.678$ is the most distant object in the sample. Figure 4 shows that the moderate-redshift galaxies observed here (11 with $z>0.4$) have a very similar size-luminosity relation to low-redshift objects. This implies that galaxies’ sizes and absolute magnitudes have not changed very significantly since over this redshift range, or at least that any general change in galaxy sizes has been offset by a corresponding change in absolute magnitudes, so that the population has shifted with redshift along, rather than perpendicularly to, the Holmberg locus.

The morphologies, colours and [OII] equivalent widths of the individual galaxies in this sample appear to be broadly consistent with those of various types of z=0 galaxies as they would be seen at these redshifts. Even the three compact objects (10.2.02, 10.2.04 and 13.2.26) which have very blue colours ($b_r-r_F=0.6–0.7$) yet low [OII] equivalent widths may have a low-redshift, low-luminosity counterpart in the dwarf galaxy recently discovered by Steidel et al. (1993).

These observations do not go deep enough to detect direct evidence of tidal interactions in the form of distorted isophotes, trails, bridges and other low surface brightness features. Only the presence of close companions indicates the possibility of some interaction, and evidence linking the companions to the star-formation must necessarily be statistical. It is therefore of interest to compare the numbers of close companions around the high- and low-$W_\lambda$ objects in this sample. All five galaxies found to have close companions (10.2.11, 10.2.23, 13.2.13, 13.5.06 and 13.5.07) have $W_\lambda>20$ A. Thus five out of the seventeen $W_\lambda>20$ A objects have close companions, compared to none out of the nine $W_\lambda<10$ A objects. One possible concern about this result is that the samples observed during the two runs had quite different relative numbers of high- and low-$W_\lambda$ objects, and that the use of different filters, or different exposure times or seeing, may have made companions easier to detect in one set of data than the other. This concern can be answered by noting that the same companions are found on the I frames as on the B or V frames, and that the I frames for both runs had similar integration times and reached similar depths. Furthermore the fraction of high-$W_\lambda$ objects with close companions is also similar for the two runs.

Is the difference in the fraction with close companions statistically significant? If both high- and low-$W_\lambda$ galaxies had the same incidence of close companion (e.g. because the companions were chance projections), the maximum likelihood of observing so many companions about high-$W_\lambda$ objects and so few about low-$W_\lambda$ objects would be 4.5%. Student’s t-test rejects the hypothesis that the two samples are drawn from populations with the same mean fraction of close companions at the 1.3% level. The conclusion that around 30% of galaxies with enhanced star-formation have very close (<10 h$^{-1}$ kpc projected separation) companions, whereas fewer than 10% of low-$W_\lambda$ galaxies have similarly close companions, is thus significant but not yet compelling. However the numerical coincidence between the 30% of $W_\lambda>20$ A galaxies with close companions found here and the 40% excess in the number of $W_\lambda>20$ A galaxies found in the Colless et al. redshift survey is striking. Although the sample is small, this is the first direct evidence suggesting that interactions or mergers play a significant role in the increased fraction of field galaxies with enhanced star-formation at these redshifts.

The resolution of some objects in this notionally magnitude-limited sample into pairs of fainter objects unfortunately makes comparisons between the absolute fraction of close pairs in this sample and well-studied samples at low redshift impractical. A magnitude-limited sample of galaxies obtained at high spatial resolution is required in order to estimate the fraction of galaxies at these redshifts in which close companions are likely to be inducing star-formation, and to determine whether a greater fraction of the galaxy population are undergoing interactions than at low redshift (as suggested by Zepf & Koo 1989).

One cautionary point for future studies is that the colours of the objects with close companions were in some cases misleading, since the original photometry did not resolve the star-forming galaxy from its (significantly redder) companion. This raises a potential difficulty in interpreting the colour distributions of faint galaxies from photometry with only moderate spatial resolution if merging or interactions are an important factor.

6 CONCLUSIONS

A sample of galaxies from the redshift survey of Colless et al. (1990, 1993) have been observed at high resolution using HRCam on the CFHT. The aim was to discover whether multi-colour imaging at the best achievable ground-based resolution could provide new information about the physical processes behind the significant excess of star-forming galaxies at moderate redshifts found in recent redshift surveys. The target galaxies included a primary sample of 17 objects with [OII] equivalent widths $W_\lambda>20$A indicative of
enhanced star-formation, and a comparison sample of 9 objects with $W_\lambda<10\AA$. We obtained images in V and I or B and I with 0.5–1.0 arcsec seeing for each galaxy, and have fitted exponential disks (or, where appropriate, $r^{-1/4}$-law bulges) directly to the 2D images in both passbands in order to obtain objective information on the scalesizes (both relative and absolute) of the blue and red stellar populations. We have also searched for faint companions close to each target galaxy in order to determine whether the star-formation might be linked to interactions or mergers. Our main conclusions are as follows:

(i) The galaxies observed here, covering the redshift range $z=0.1–0.7$, have straightforward analogues amongst nearby objects, in that their colours, sizes and luminosities are consistent with those of various types of $z \approx 0$ galaxies. There is no evidence for a significant population of compact star-forming dwarf galaxies such as might be expected if the hypothesis proposed by Babul & Rees (1992) were solely responsible for the excess number of blue galaxies.

(ii) The galaxies undergoing the strongest star-formation, as indicated by the equivalent width of [OII] $3727\AA$, $W_\lambda$, display a wide range of types and absolute luminosities, from $M^*-1$ to $M^*+5$. In most the blue scalelengths are comparable to or larger than the red scalelengths, indicating global star-formation across the disk.

(iii) Significantly, 5/17 galaxies with $W_\lambda>20\AA$ have fainter companions lying within a projected distance of $10 \, h^{-1} \, \text{kpc}$, compared to 0/9 with $W_\lambda<10\AA$. This fraction is very similar to the fractional excess of such galaxies observed in the redshift survey of Colless et al., suggesting a direct connection between interaction and star-formation.

(iv) Notwithstanding this evidence for interaction-related evolution, there are several apparently isolated galaxies with large $W_\lambda$ and three low-$W_\lambda$ galaxies with blue colours and unresolved morphologies. Larger samples are need to determine the importance of such systems in explaining the excess faint blue galaxy population.

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