The nature of the faint galaxies in the Hubble Deep Field

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ABSTRACT

We present a study of the galaxies found in the Hubble Deep Field (HDF). A high proportion of HDF galaxies are undergoing a strong episode of star formation, as evidenced by their very blue colours. A wide range of morphological types is found, with a high proportion of peculiar and merger morphologies.

Fitting the multiband spectra with redshifted spectral energy distributions of galaxy types E to H II, we predict the spectral types and redshifts of galaxies detected in the HDF. We predict a median redshift of 2.1, with 72 per cent having $z > 1$ and 5 per cent with $z > 3$. The $I$-band absolute magnitude distributions as a function of galaxy type show a plausible trend of decreasing luminosity towards later types. The derived $I$-band luminosity function agrees well with that from the Canada–France survey for $z < 1$, and shows evidence for luminosity evolution (at $M_I < -21$) in the range $2 < z < 3$, smaller than the rate seen in quasars and starburst galaxies.

We have predicted infrared and submillimetre fluxes, assuming that most of the galaxies are undergoing a strong starburst. Several planned space-borne and ground-based deep surveys are capable of detecting interesting numbers of HDF galaxies.

Key words: galaxies: evolution – galaxies: luminosity function, mass function – cosmology: observations.

1 INTRODUCTION

In 1995 December an area of five square arcminutes at RA $12^h 36^m 49.4^s$, Dec. $+62^\circ 12' 58''$ (J2000) was surveyed by the Hubble Space Telescope (HST) to an unprecedented depth (Williams et al. 1996). This survey, referred to as the Hubble Deep Field (HDF), consists of three wide field areas, each of size 75 arcsec square, carried out by the Wide Field Planetary Camera 2 (WFPC2), and a smaller area of 35 arcsec square covered by the planetary camera. The HDF is over 1 mag deeper than the deepest surveys previously done by the HST, and is carried out in four bands: F300W (300 nm), F450W (450 nm), F606W (600 nm) and F814W (800 nm), roughly corresponding to the $UBVI$ system. The field is chosen to have a representative number density for galaxies and to be devoid of bright stars.

One of the main applications of the HDF is to study the nature of the faint population of galaxies found in ground-based optical surveys. Recent models, interpreting deep counts of galaxies, have invoked bursts of star formation, merging of galaxies (Broadhurst, Ellis & Shanks 1988), dust obscuration (Franceschini et al. 1994), the presence of a new population of dwarf galaxies (Cowie, Songaila & Hu 1991) and a steep faint-end slope for the local luminosity function (Koo, Gronwall & Bruzual 1993). The degree to which we can discriminate between these competing scenarios is limited by the size and depth of the available surveys, the morphological type information obtained from them at deep levels, and the wavelength at which they have been carried out. The HDF and its follow-up spectroscopic observations are expected to disentangle some of these scenarios, and provide a natural extension to ground-based optical surveys (Smail et al. 1995; Lilly et al. 1995). Recently, Abraham et al. (1996) performed morphological type classification of the HDF galaxies with $I < 25$ mag and concluded that, at this depth, the classical Hubble system fails to explain the large fraction of peculiar/irregular/merger galaxies observed in the HDF.

In this study, we explore the nature of the faint galaxy population observed in the HDF. Using the available multiband information, we predict photometric redshifts and spectral types of the galaxies detected in the HDF. These are used to make a preliminary study of the distribution of the faint blue population in redshift and luminosity space. A promising aspect of future studies of the HDF is follow-up at longer infrared and submillimetre wavelengths. We make predictions of the fluxes expected at these wavelengths, assuming that most of the galaxies are undergoing a
major episode of star formation. We assume \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0.5 \) throughout this paper.

The catalogue generation is discussed in the next section. Section 3 presents a study of the faint blue galaxy population in the HDF, followed by estimates of photometric redshifts and spectral types of the galaxies in Section 4. The Hubble diagram and luminosity function of the HDF galaxies are presented in Section 5, and prediction of their infrared and submillimetre fluxes in Section 6. Conclusions are summarized in Section 7.

2 CREATION OF A GALAXY CATALOGUE

We have followed two different approaches to generating a galaxy catalogue. Our first approach was to generate independent galaxy catalogues in all four bands. Object identifications and star/galaxy separations were performed, using the PISA software in the Starlink environment. These were further confirmed using the FOCAS/IRAF source identification package. Aperture photometry was then carried out with PHOTOM on all the identified galaxies, using an aperture size of 0.5-arcsec radius. For 0.5 < \( z < 3 \), this corresponds to a linear diameter of 4.0 ± 0.4 (\( H_0/50 \)) \( ^{-1} \) kpc. The photometry zero-points provided by the Space Telescope Science Institute (STScI) were used. The catalogues for different bands were cross-correlated, and objects with detections in more than one band were identified. A total of 1761 galaxies were identified in the three WFPC2 fields. However, this approach resulted in almost half the galaxies having detected magnitudes in only one or two bands.

Our second approach was to take all the detections in the \( I \) band and then carry out photometry in the three other bands, using the \( I \)-band positions, again with a 0.5-arcsec aperture. This resulted in a catalogue with 1611 galaxies detected in \( I \) and \( V \), of which 1495 were detected in \( B \) and 490 in \( U \). The thresholds for reliable detection were set, after some iteration, at \( V = 30 \), \( B = 30 \), \( U = 26.5 \) mag. This is the primary catalogue which we have used in this analysis. The magnitudes at which serious incompleteness sets in are \( I \sim 28 \), \( V \sim 28.5 \), \( B \sim 28.5 \), \( U \sim 26 \), with the completeness limit for statistical purposes being about 0.5 mag brighter than these values.

For the HDF bright galaxies studied by van den Bergh et al. (1996), we have re-done the photometry with an aperture of 3-arcsec radius. We find excellent agreement between the two sets of magnitudes, with an rms scatter of 0.06 mag.

3 THE FAINT BLUE GALAXY POPULATION IN THE HDF

The \( (B - V) - (U - B) \) colour–colour diagram for different morphological types of galaxies, detected in all four bands, is compared with model predictions in Fig. 1. Only the bright galaxies \( (I < 25 \) mag) with available visual type classifications from van den Bergh et al. (1996) are used. We also carried out independent morphological type classification and found a high degree of agreement with that of van den Bergh et al. (1996). The types are divided into four categories: E/S0s, spirals, irregulars and mergers, as classified by van den Bergh et al. (1996). We have predicted the synthetic colours at different redshifts using the observed spectral energy distributions (SEDs) of elliptical, spiral (Sbc) and \( H\alpha \) galaxies. The SEDs of elliptical and spiral galaxies are taken from Yoshii & Takahara (1986) and that for the \( H\alpha \) galaxies is from the observed continuum of Tol 2142–416 (Calzetti & Kinney 1992). The study of the UV continua of \( H\alpha \) galaxies by Kinney (1993) indicates that the UV spectrum of this galaxy is typical of \( H\alpha \) galaxies. The predicted colours for \( z > 1.5 \) are based on extrapolation of the observed/model continua to Ly\( \alpha \), beyond which we assume the continua to drop as \( f \propto \lambda^2 \) (see below). The predicted colours are calculated in the HST filters.

The range of predicted colours agrees with the observed data. The blue galaxies \( (B - V < 0.5) \) are mainly dominated by mergers (67 per cent of the mergers in Fig. 1 have \( B - V < 0.5 \)) and cover a range of \( U - B \) colours \( (-1 < U - B < 1) \), locating them at different redshifts. These are reasonably well fitted by our galaxy models, shifted to high redshifts \( (z \sim 1.5 - 3) \). According to these models, most of the mergers take place at relatively high redshifts \( (z \sim 2) \). At these redshifts, the \( U - B \) colours rapidly increase as Ly\( \alpha \) comes into the \( U \) band. However, the redder galaxies \( (B - V > 0.5) \) appear to cover a large redshift range \( (0 < z < 3) \), with some being local objects \( (0 < z < 0.5) \).

4 PHOTOMETRIC REDSHIFT ESTIMATES

Since most of the HDF galaxies are too faint for spectroscopic redshift measurements with even the largest ground-based telescopes, it is useful to estimate their photometric redshifts, using the available multiwavelength data. Such studies have generally been carried out on samples with a much more modest range of redshifts than is present in the HDF (e.g. Koo 1986; Connolly et al. 1995). The \( U \)-band data are crucial for allowing redshift estimates in the range \( 1.5 - 3 \).

The observed, rest-frame SEDs for six different types of galaxies (E/S0, Sab, Sbc, Scd, Sdm from Yoshii & Takahara 1986; \( H\alpha \) from Calzetti & Kinney 1992, as above) have been used to produce a grid of SEDs in the log \( (1 + z) \) range 0.01 to 0.7 in intervals of 0.01, i.e. 0 < \( z < 4 \). These are then compared with the observed SEDs for the HDF galaxies and the best fit selected by least squares. The numbers of galaxies with SED types E/S0, Sab, Sbc, Scd, Sdm and \( H\alpha \) are found to be 295, 239, 128, 169, 307 and 475 respectively.

The uncertainty in the photometric redshifts can be estimated by calculating the value of \( \chi^2 \) as a function of \( z \) for each galaxy type. For an assumed magnitude error of ± 0.06 mag for brighter \( (I < 25 \) mag) galaxies in each band, the typical formal uncertainty in \( (1 + z) \) ranges from 5 to 15 per cent for a galaxy detected in all four bands, with only a minority giving acceptable solutions for more than one galaxy type. However, for objects detected in only three or two bands, the uncertainty in redshift increases and there is often more than one acceptable redshift/galaxy type solution. The redshift distribution for the whole sample as a function of galaxy type is shown in Fig. 2. No obvious bias is present and, on the whole, there is a smooth distribution of redshifts for each galaxy type. Moreover, the range in redshift, covered by each morphological type, is consistent with that indicated by Fig. 1, using synthetic models and visual type classifications.

Figure 1. $(B - V)$ versus $(U - B)$ for the HDF galaxies with $I < 25$ mag with visual type classifications from van den Bergh et al. (1996). Predicted loci as a function of redshift, for $0 < z < 3$, are shown for E (dotted), Sbc (short-dashed), Sdm (long-dashed) and H\,II (solid) galaxies.

The predicted redshift distribution depends strongly on the assumptions made about the UV spectra of galaxies. The blue colours of the majority of the faint HDF galaxies strongly support the idea that these are redshifted galaxies undergoing a burst of star formation. The galaxy SEDs of Yoshii & Takahara (1986), which are a combination of observation and synthetic models, incorporate continua rising towards the UV ($f_\lambda \sim \lambda^{-2}$) for a range of galaxies of type Sdm and Sab and, on the basis of IUE observations of NGC 4649, of type E/S0. Since many HDF galaxies are found to have blue $(V - I)$ colours but relatively red colours at shorter wavelengths $(U - B$ or $B - V)$, it is likely that we are seeing Lyman continuum or Lyman limit absorption redshifted into the observed bands. Therefore we have explored two models for the extreme UV continua. First, we introduced an abrupt cut-off at the Lyman limit (cf. the protogalaxy model of Meier 1976). This resulted in a strong peak in the redshift distribution at $z \sim 2$ owing to galaxies having blue $(V - I)$ and $(B - V)$ but red $(U - B)$ colours. However, observations of high-redshift quasars (e.g. Steidel & Sargent 1987) suggest a more gradual extinction of the Lyman continuum starting shortward of Ly$\alpha$. Therefore we have modified the above model of approximating the models of Giallongo & Trèvese (1990), assuming $f_\lambda \sim \lambda^{-1}$ for $\lambda < 912$ Å for all galaxy types. This assumption gave a much smoother redshift distribution, extending to higher redshifts, and is the model that we have adopted in this paper. For galaxies with $I < 20$, we have allowed a maximum redshift of 1, and for galaxies with $I = 20-23$ we have allowed a maximum redshift of 3. These restrictions eliminated one or two implausible aliases among the brighter objects.

Spectroscopic redshifts have been measured for a number of HDF galaxies by Cohen et al. (1996) and Cowie (1996), and for a few high-redshift candidates by Steidel et al. (1996). These are compared with our photometric redshifts in Fig. 3. The agreement is quite impressive. The $(\xi_{\text{phot}} - z_{\text{spec}})/(1 + z_{\text{spec}})$ values have been estimated and found to have an rms scatter of 0.14 (for 50 objects with available spectroscopic redshifts), implying $\pm 14$ per cent (1σ) accuracy in our $(1 + z)$ estimates. Although some individual estimates are likely to be aliased, our photometric redshifts appear to have statistical validity over the range $0.1 < z < 3$.

A large number of galaxies in our HDF catalogue are found to have blue $(V - I)$ and red $(U - B)$ colours, for which we estimate redshifts in the range $1.5-3$. There are also a few (a total of 11 galaxies) that are blue in $(V - I)$ but red in $(B - V)$, with no detection in $U$. These are good candidates for the Lyman continuum redshifting into the $B$ band, so that $z > 3.6$. The distinctions of galaxy type at high
Figure 2. Redshift distribution as a function of galaxy spectral types. There is a reasonably smooth distribution of types with redshift, with no obvious bias present.

redshift, generated in our model by differences in the $\lambda > 912$ Å continuum slope, are perhaps slightly artificial. These galaxies require further morphological and photometric study.

At the redshifts estimated for the HDF galaxies, the $K$-corrections are expected to be significant. The type-dependent $K$-corrections in the $I$ band are estimated for each of the six morphological types considered here, using their respective SEDs as discussed above. These are then employed to correct the absolute magnitudes of galaxies for the redshift effect, using their respective spectral types discussed above. The $I$-band absolute magnitude distributions $M_I$ for each galaxy type are presented in Fig. 4. These show a highly plausible trend of decreasing absolute magnitude towards later type galaxies. A large number of objects in the HDF are classified here as star-forming H II galaxies, covering a range of absolute magnitudes.

5 I-BAND HUBBLE DIAGRAM AND LUMINOSITY FUNCTION

The $I$-band Hubble diagram for the whole HDF galaxy sample is shown in Fig. 5, together with the predicted curve for an Sbc galaxy with $M_I = -20$. This diagram appears to be a plausible extension to fainter magnitudes of the corre-

Figure 3. Spectroscopic redshift versus photometric redshift estimated here. The spectroscopic redshifts for nearby galaxies are taken from Cowie (1996) and Cohen et al. (1996), and those for high-redshift objects are from Steidel et al. (1996) observations. Lines connected to crosses indicate cases where a more accurate redshift resulted from using $U$-band detections fainter than our magnitude limit of $U = 26.5$ mag.

Figure 4. Absolute magnitude distribution as a function of galaxy spectral type. There is a plausible trend of decreasing peak luminosity towards later types.
Figure 5. I-band Hubble diagram for the whole sample (1619 galaxies). Different spectral types are identified as follows: E/S0 (●); Sa/Sab (♦); Sb/Sbc (★); Sc/Scd (○); Sd/Sm (×); H (□). The line is the predicted relation for an Sbc galaxy with $M_I = -20$ mag.

The I-band completeness limit of the HDF is estimated as $I = 27.5$ mag. For the 1353 galaxies brighter than this limit, we have calculated the luminosity function in three different redshift intervals (Fig. 6). The I-band magnitudes are corrected to the rest frame, using the type-dependent K-corrections estimated in Section 4. The luminosity function for $z < 1$ shows remarkably good consistency with that found by Lilly et al. (1995) for the Canada–France survey to $I = 22.5$ mag. They agree both in the normalization and in the steep faint-end slope, which we find to be $\alpha = 1.3$ at $M_I > -22$, caused mainly by Sdm and H n galaxies. These objects also dominate the faint-end slope of the luminosity function ($-23 < M_I < -19$) in the range $1 < z < 2$ (Fig. 6). They have a space density (at $M_I = -21$ mag) similar to that of the local population ($z < 1$) of H n galaxies and late-type spirals. However, the bright end of the luminosity function ($M_I < -23$ mag) at $2 < z < 3$ in Fig. 6 is dominated by optically luminous elliptical and Sab galaxies, as is clear from their absolute magnitude distribution in Fig. 4. At these

Figure 6. I-band luminosity function for three redshift intervals. The completeness limit is set at $I = 27.5$ mag. There is a clear increase in the number density of luminous galaxies at $z > 2$. Error bars correspond to a Poisson distribution.

redshifts, the observed wavelength (\( I \) band) at which the sample is selected roughly corresponds to the rest-frame \( U \) band (2000–2600 Å). In our model, these galaxies are undergoing strong bursts of star formation, producing their large optical luminosities and hence making them detectable at these short wavelengths.

There is no significant evolution of the luminosity function to \( z \sim 2 \). However, the rate of evolution increases in the range \( 2 < z < 3 \) but is still smaller than the rate of luminosity evolution found for quasars (Boyle et al. 1988) and starburst galaxies (Saunders et al. 1990; Rowan-Robinson et al. 1993). Although some optical galaxy redshift surveys have claimed to be inconsistent with luminosity evolution (Broadhurst et al. 1988; Colless et al. 1990), recent studies have begun to find hints of luminosity evolution in the galaxy luminosity function (Colless 1995; Lilly et al. 1995).

6 PREDICTION OF INFRARED AND SUBMILLIMETRE FLUXES

It is a goal for many space projects and ground-based telescopes, existing or planned, in the infrared and submillimetre (e.g. ISO, SCUBA, FIRST), to detect starburst galaxies at high redshift. It is therefore of great interest to predict the infrared and submillimetre fluxes for the HDF galaxies.

The very blue colours of most of the HDF galaxies suggest that they are undergoing a strong episode of star formation, and this is supported by the high incidence of peculiar and merging morphologies. We assume that the SEDs of these galaxies at infrared and submillimetre wavelengths can be well represented by the standard starburst model of Rowan-Robinson & Efstathiou (1993). For the relative normalization between far-infrared and optical, we make an assumption similar to that made by Pearson & Rowan-Robinson (1996), namely that \( F = v\Sigma_{s}(60 \mu m)/v\Sigma_{s}(0.8 \mu m) = 10 \) in the rest frame. These authors claim that, if the proportion of the total bolometric power in a starburst, emerging in the optical–UV, were greater than about 5–10 per cent, then the optical galaxy counts at \( B = 21–23 \) mag would be violated (for a 60-\( \mu m \) luminosity function normalized to fit the \( IRAS \) 60-\( \mu m \) source counts).

With these assumptions, we predict the flux for HDF galaxies at infrared or submillimetre wavelengths, allowing for their redshift and galaxy type. Table 1 gives the number of HDF galaxies expected brighter than a given flux density at wavelengths of interest to ISO, SCUBA and FIRST. It appears that deep integrations by the ISO, SCUBA and FIRST are capable of detecting a number of HDF galaxies.

We have also calculated the total background intensity expected from these galaxies at each wavelength (see Table 1). The resulting spectrum is similar in shape and amplitude (to within a factor of 2) to that predicted by Pearson & Rowan-Robinson (1996; see also Oliver, Rowan-Robinson & Saunders 1992; Rowan-Robinson & Pearson 1996), consistent with the picture that the majority of the HDF galaxies belong to the population of strongly evolving starburst galaxies previously studied in far-infrared and sub-mJy radio surveys.

7 CONCLUSIONS

The conclusions of this study can be summarized as follows.

(i) A wide range of morphological types is found in the HDF (from ellipticals to \( H \) \( II \) galaxies), spanning a range in redshift (0 < \( z < 4 \)). About 67 per cent of the mergers are found to have blue colours (\( B - V < 0.5 \)) at \( z \sim 2 \). The redder galaxies (\( B - V > 0.5 \)) cover a larger range in redshift, consisting of many nearby objects.

(ii) Fitting the multiband spectra with redshifted SEDs of galaxy types E to \( H \) \( II \) gives a plausible distribution of galaxy types, redshifts and absolute magnitudes. We find a median redshift of 2.1, with 72 per cent having \( z > 1 \) and only 5 per cent with \( z > 3 \). The \( I \)-band absolute magnitude distributions as a function of galaxy type show the expected trend of decreasing luminosity towards later type galaxies.

(iii) The derived \( I \)-band luminosity function agrees remarkably well with that from the Canada–France survey (Lilly et al. 1995) for \( z < 1 \). It does not show a strong luminosity evolution in the range 1 < \( z < 2 \). However, there is evidence for the evolution of the luminosity function for 2 < \( z < 3 \) but the rate of evolution is smaller than that observed for quasars and starburst galaxies.

The luminosity function at 1 < \( z < 2 \) is mainly dominated by blue, star-forming spirals with a space density similar to the \( z < 1 \) galaxies. The bright end of the luminosity function (\( M_{I} < -23 \) mag) at 2 < \( z < 3 \) is dominated by optically luminous early-type galaxies. These objects are undergoing strong bursts of star formation and hence are detectable at shorter wavelengths (2000–2600 Å).

(iv) We have predicted the infrared and submillimetre fluxes, assuming that most of the galaxies are undergoing a strong starburst. Several planned space-borne and ground-

Table 1. Predicted cumulative numbers of HDF galaxies as a function of infrared and submillimetre flux densities.

<table>
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<th>15</th>
<th>60</th>
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<th>200</th>
<th>400</th>
<th>800</th>
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<td></td>
<td></td>
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</tr>
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<td>0</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>36</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100 ( \mu Jy )</td>
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<td>2</td>
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<td>203</td>
<td>430</td>
<td>317</td>
<td>77</td>
<td>13</td>
</tr>
<tr>
<td>10 ( \mu Jy )</td>
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<td>555</td>
<td>979</td>
<td>1257</td>
<td>898</td>
<td>431</td>
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</tr>
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<td>1613</td>
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based deep surveys are capable of detecting interesting numbers of HDF galaxies.

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