Sensitive optical surveys have revealed\textsuperscript{1} a large population of ‘faint blue galaxies’ which are believed to be young galaxies\textsuperscript{2}, observed close to their time of formation\textsuperscript{2}. But there has been considerable uncertainty regarding the epochs at which these galaxies are observed, owing to the difficulties inherent in determining spectroscopic redshifts for very faint objects. Here, by modelling the counts and colours of galaxies at the faintest detection limits, we show that the faint blue galaxies are likely to lie at high redshift ($z \approx 2$). This conclusion holds regardless of whether the Universe is assumed to be open or at the critical density (flat). In an open universe, the data are consistent with galaxy models in which star formation rates decay exponentially with decreasing redshift, whereas the assumption of a flat universe requires the addition of a population of galaxies which are seen only at high redshift.

We have measured galaxy counts and colours in the Deep Field\textsuperscript{3} recently observed by the Hubble Space Telescope (HST) to $U = 27^m$, $B = 29^m$, $R = 28.5^m$ and $I = 28^m$. The HST
data covers 5.3arcmin$^2$ and the exposure times were $\approx 25$ hrs in each of the BRI bands and $\approx 47$ hrs in the U band. Similar techniques, adjusted for the smaller image size, were used to analyse the HST data as we have previously used to analyse deep ground-based images$^{4,5}$. Taking these deepest galaxy count data together with the results of recent galaxy redshift surveys at the spectroscopic limit of the Keck Telescope$^{6,7}$, reveals the clearest picture so far of the Universe at faint magnitudes.

The derived HST B galaxy number counts are shown in Fig. 1, together with those from other work, including the deepest ground-based counts from the William Herschel Telescope (WHT) to $B = 28.^{m}2$. The HST and WHT results are seen to be in good agreement to this limit, with the HST counts extending $\approx 1^{m}$ fainter. Figure 1 also shows the HST counts in the I band. In this band the HST data extends about $10\times$ deeper than previous data, because of the higher HST resolution and the fainter background sky. Although HST has as yet no K band imaging capability we also summarise in Fig. 1 the deepest ground-based K counts, including new data from the U.K. Infrared Telescope (UKIRT). The K counts now appear to be reasonably well defined in the range $13^{m} < K < 24^{m}$.

We first compare the count data with non-evolving models. In the modelling we assume throughout a Hubble Constant of $H_o = 50kms^{-1}Mpc^{-1}$ but our main conclusions below are insensitive to this assumption. As can be seen from Fig. 1, the non-evolving models increasingly underestimate the optical counts at faint magnitudes. However, the magnitude at which the ‘faint blue galaxy’ excess becomes apparent is dependent on the normalisation of the models at bright magnitudes. With the high normalisation adopted here, non-evolving models give a reasonable representation of the bright counts and redshift distributions in the range $18^{m} < B < 22.^{m}5^{1,4,5,8,9}$ and also to individual counts of
spiral and early-type galaxies at similar magnitudes\textsuperscript{10,11}. As a consequence, the B galaxy count then only shows evidence for strong evolution in the range $B > 23^m$. Also the high normalisation allows non-evolving models with deceleration parameter $0.05 < q_o < 0.5$, to fit the K counts from $K = 15^m$ to the faintest count limit at $K = 24^m$. This is as expected since evolved, young star populations are expected to affect galaxy light less in the infrared than in the blue.

To fit the optical counts, we then consider simple evolutionary models from Bruzual & Charlot\textsuperscript{12} where galaxy star-formation rates rise exponentially with look-back time. In such models, the galaxy light at early times is generally dominated by luminous, blue stars but at later times, when these stars fade and the star-formation rate slows, the galaxy light dims and reddens. These models are known to fit the B counts in the range $18^m < B < 25^m$\textsuperscript{1,4,5,8,9}. But previous faint galaxy redshift surveys at $B < 24^m$ presented a problem for such models, as they predict a high redshift tail of evolved, luminous galaxies which was unobserved in these surveys\textsuperscript{13}. However, these surveys were frequently only $\approx 60\%$ complete and the galaxies with unidentified redshifts were usually blue. Recently Cowie et al\textsuperscript{6,7} have used the Keck 10m telescope to make a new $B < 24^m$ galaxy redshift survey with $> 80\%$ completeness and have detected such a high redshift galaxy component, supporting the basic viability of these models (see Fig. 2). An extended high redshift tail is also consistent with the low galaxy clustering amplitude observed\textsuperscript{9} at $B > 23^m$.

A further new development is that the latest version of the preferred spiral galaxy evolution model\textsuperscript{12} now permits more brightening at high redshift, while still reproducing the blue colours of spirals at the present day\textsuperscript{14}. Combined with the steep luminosity function of spirals\textsuperscript{8} and assuming a small amount of internal dust\textsuperscript{14−16}, this enables us to obtain
a good fit to the high redshift tail of the Keck, number-redshift distribution, \( n(z) \), at \( 22.5^m < B < 24^m \) (see Fig. 2) and to other redshift survey results\(^{17}\). In the low \( q_o \) case, this spiral dominated model then also produces a reasonable fit to the optical counts to \( B \approx 27^m \) and \( I \approx 26^m \) (see Fig. 1). Although the model underestimates the optical counts at fainter magnitudes, this discrepancy is probably still within the combined data and model uncertainties. In the \( q_o = 0.5 \) case, the spiral luminosity evolution model only fits the optical data to \( B \approx 25^m \) and \( I \approx 23^m \) and then more seriously underestimates the counts at fainter magnitudes. Thus, the HST data confirms the previous ground-based result\(^{1,4,5,18}\) that if \( q_o = 0.5 \), then there is not enough spatial volume at high redshifts to allow simple luminosity evolution models to fit the high galaxy counts at \( B > 25^m \). This confirmation is important because confusion corrections are much smaller in the high resolution HST galaxy counts than in previous ground-based data.

We have already noted that the faint K counts seem less affected by evolution and this is supported by the new Keck redshift data\(^6,7\), where non-evolving models again give a good fit to the \( n(z) \) relation for \( 18^m < K < 19^m \) (ref. 7). Since non-evolving models imply that, at \( K < 20^m \), the majority of galaxies are early-types, this suggests that early-type galaxies may be little affected by either dynamical(merging) or luminosity evolution. Indeed, although the effect of passive evolution of early-type galaxies with a Salpeter Initial Mass Function (IMF) slope (\( x = 1.35 \)) is small at \( K(< 0.7^m \text{ at } z = 1) \), it is still big enough to make the predicted Keck \( n(z) \) appear too extended at \( 18^m < K < 19^m \). If the result is not due to incompleteness, then the amount of K evolution can be reduced to acceptable limits by assuming a more dwarf dominated IMF(\( x = 3 \)) for early-type galaxies. While awaiting more complete K surveys, we have adopted this dwarf-dominated IMF for early types throughout...
To improve the fit of the $q_0 = 0.5$ model to the faint optical counts we consider a model with an extra population of high redshift galaxies which have a constant star-formation rate from the formation epoch till $z=1$ ($\approx 4Gyr$ after formation with our assumed $H_o$). The Bruzual & Charlot$^{12}$ model shows that at $z \lesssim 1$ the galaxy then rapidly fades by 5 magnitudes in B to form a red (dE) galaxy by the present day. This model is in the spirit of previously proposed ‘disappearing dwarf’ count models$^{19}$ and it gives a good fit to the faint B,I,K counts and the Keck n(z) data (see Figs. 1 and 2).

We next test these models against the faint galaxy colour distributions in the Hubble Deep Field. The presence of broad features in galaxy spectra allows tests to be made of the predicted galaxy redshifts. One approach is to use the HST broad band photometry as a rough galaxy spectrum and then derive redshifts for individual galaxies using local galaxies as templates$^{20}$. Here we follow the different approach of simply comparing our evolutionary model predictions to the observations of faint galaxy colours. We see in Fig.3 that our predicted $U' - B' : B' - I'$ model tracks, ie the loci traced by model galaxy colours as they change with redshift, compare well with the observed colours for $B' < 27.5$ galaxies. (Primed letters here denote the natural HST magnitude system). In particular, the redshifting of the Lyman $\alpha$ forest/break$^{21}$ absorption features through the $U'$ band causes the model $U' - B'$ colours to move sharply redwards at $B' - I' \approx 0.7$ and the same effect is clearly seen in the data. The colours of 45 brighter $B \approx 24$ galaxies with Keck redshifts are also shown in Fig. 3 and are also found to agree well with their predicted colours. (The equivalent $B' - R' : R' - I'$ graph is shown as supplemental information at the Nature web site).
The above predictions show that, for the majority of faint galaxies, $U' - B' < 0$ is predicted to correspond to $z < 2$ galaxies and $U' - B' > 0$ corresponds to $z > 2$ galaxies. We find that the proportion of galaxies with $U' - B' > 0$ (including those undetected in $U'$) rises to $47 \pm 7\%$ of the total at $27^m < B < 28^m$, indicating that the redshift distribution may peak at $z \approx 2$. This fraction is matched very well by both the $q_o = 0.05$ model which predicts 47% with $U' - B' > 0$ at the same limit and the $q_o = 0.5$, disappearing dwarf (dE) model which predicts 43%. We have also considered another $q_o = 0.5$ model which assumes an extra population of low redshift dwarf spirals (dSp) which evolve more slowly according to our standard exponential model for spiral luminosity evolution$^{12}$. Although this model also gives an improved fit to the counts, it predicts too few high redshift ($U' - B' > 0$) galaxies (28%) for compatibility with the faint HST data.

These conclusions are confirmed by consideration of the $B' - R' : R' - I'$ colour-colour plot in Fig. 4. Fig. 4a shows the predicted tracks of the galaxy types with redshift, as in Fig. 3. Also plotted are the galaxies with $U' - B' > 0$ and $R' < 27.5^m$; these are expected to have $z > 2$ by the above arguments and it can be seen that their position on the $B' - R' : R' - I'$ tracks is entirely consistent with their lying in this redshift range. We regard this as crucial confirmation that our models are indicating consistent redshifts for galaxies in $U' - B'$ and $B' - R' : R' - I'$ independently. Figs. 4b,c,d then show the HST data (dots) at $R' < 28^m$ compared to the predicted galaxy number contours for the open and closed models, based on the tracks shown in Fig. 4a. Both the $q_o = 0.05$ and the $q_o = 0.5$ dE model contours give a reasonable fit to the data which seem to peak at $B' - R' \approx 0.3$, $R' - I' \approx 0.3$, corresponding to $z \approx 2$ for all galaxy types. However, the $q_o = 0.5$ dSp model contours peak away from this point at $B' - R' \approx 1$, $R' - I' \approx 1$ which corresponds to $z \approx 0.5$
for the dwarf spiral galaxies and we conclude that the galaxy redshift distribution in this model is skewed to too low redshifts to be compatible with the colour data. This does not mean that the above ‘disappearing dwarf’ model is unique in allowing a fit to be obtained with $q_o = 0.5$; other possibilities such as merging models may also exist. However, it does suggest that, in any model, the star-forming phase has to be at $z \approx 2$ for consistency with the faint galaxy colours in the Hubble Deep Field.
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A. Campos is now at Instituto de Astrofisica de Andalucia, CSIC, Spain.
The B (Johnson) and I (Kron-Cousins) galaxy counts from the HST Deep Field (F450W, F814W) data\(^3\) compared to counts from the WHT, UKIRT and elsewhere (refs. 1,4,5,10,11,22-29) and various models. Also shown are deep K band galaxy counts from ground-based data. The I band counts have been multiplied by a factor of 10 and the K band counts have been multiplied by a factor of 100 for clarity. (The HST U and R counts are presented as supplemental information at the Nature web site.) The model luminosity function parameters and other details of the modelling procedure are given elsewhere\(^4,5\). The galaxy luminosity evolution with redshift is computed from Bruzual & Charlot\(^{12}\) isochrone synthesis models, using the appropriate passbands. We assume galaxy ages of 16 and 12.7 Gyr in the cases \(q_o = 0.05, 0.5\). We adopt a dwarf dominated IMF (\(x=3\)) with an exponentially increasing star-formation rate of time scale, \(\tau = 2.5 Gyr\), for E/SO/Sab galaxies and a Salpeter IMF (\(x=1.35\)) with an exponentially increasing star-formation rate of time scale, \(\tau = 9 Gyr\), for Sbc/Scd/Sdm galaxies. The latter are also assumed to have internal dust absorption at \(z = 0\) of \(A_B = 0.3^m, A_I = 0.11^m, A_K = 0.03^m\). We take an absorption law inversely proportional to the wavelength \(\lambda\), \(A_\lambda \propto 1/\lambda\) to approximate the effect of redshift on the internal dust absorption. The models also include the effect of Lyman \(\alpha\) forest/break absorption\(^{23}\). Spiral evolution dominates these models in the B and I bands. The \(q_o = 0.05\) evolving model gives a good fit to \(B \approx 27^m, I \approx 26^m\), whereas the \(q_o = 0.5\) model only fits to \(B \approx 25^m, I \approx 23.5^m\). The fit of the \(q_o = 0.5\) model is improved when an extra high redshift galaxy population (dE) with constant star-formation rate at \(z > 1\) and rapidly fading at \(z < 1\) is invoked. The Schechter luminosity function parameters of the
dE population at z=0 are $M^*_B = -16^{m}.0$, $\alpha = -1.2$ and $\phi^* = 0.019\text{mag}^{-1}\text{Mpc}^{-3}$. The K galaxy counts, in contrast to the B and I counts, are well fitted by non-evolving models.

**Figure 2.**

The galaxy number-redshift distribution, $n(z)$, for $22^{m}.5 < B < 24^{m}$ implied by new redshift data acquired on the Keck Telescope$^{6,7}$. The observed $n(z)$ is clearly more extended than the non-evolving models with either $q_0 = 0.05$ or $q_0 = 0.5$. The extended redshift distribution is well fitted by our evolutionary models whose parameters are described in the Fig. 1 legend.

**Figure 3.**

Dots represent the $U' - B' : B' - I'$ colours of $B' < 27^{m}.5$ galaxies in the Hubble Deep Field. Primed letters for magnitudes indicate that here we are using the natural HST magnitude system, with zeropoint set at an A0V star. The arrows represent detection upper limits, mainly galaxies which are undetected in $U'$. The $U' - B'$ colours move sharply redwards at $B' - I' \approx 0.8$ due to the Lyman $\alpha$ forest/Lyman break passing through the $U'$ band. The predicted tracks are the $q_0 = 0.05$ evolutionary models for each morphological type as detailed in the caption to Fig. 1, modulated in the case of Sbc/Scd/Sdm types by our assumed internal dust absorption of $A'_U = 0.45$, $A'_B = 0.3$, $A'_I = 0.11$ and in the case of all galaxies by the Lyman $\alpha$ forest absorption. The models used in the $q_0 = 0.5$ case (not shown) show a very similar behaviour, even for the rapidly fading dE type. The z=1 and z=2 labelled positions on the tracks indicate the colours of model E/SO and Sdm galaxies at these redshifts. The remaining symbols represent the colours of 45 brighter
galaxies with Keck spectroscopic redshifts are also shown and these agree well with the predicted colours for these galaxies. It can also be seen that $U' - B' < 0$ is predicted to correspond to galaxies with $z < 2$ and $U' - B' > 0$ to galaxies with $z > 2$.

Figure 4a.

The $q_o = 0.05$ evolutionary models’ $B' - R' : R' - I'$ tracks with redshift, as a function of galaxy morphological type. Primed letters for magnitudes indicate that here we are using the natural HST magnitude system, zeropointed to an A0V star. The tracks are modulated by our assumed internal dust and Lyman $\alpha$ forest/break absorption. A filled symbol marks each galaxy type’s colour at zero redshift. The open symbols mark the galaxy type’s colour at unit intervals in redshift for E/So and Sdm galaxies. Galaxies with $B' - R' = 0.3$ and $R' - I' = 0.6$ have $z \approx 2$. The same is true for the $q_o = 0.5$ models, even for the rapidly fading dE type (not shown). The dots indicate the colours of galaxies with $R' < 27.5$ and $U' - B' > 0$ which are predicted to have $z > 2$. Their position in the independent $B' - R' : R' - I'$ plane is consistent with this prediction.

Figure 4b.

Dots represent the $B' - R' : R' - I'$ colours of $R' < 28$ galaxies in the Hubble Deep Field. These show the same horse-shoe shaped track as expected from the models in Fig. 4a. The contours represent the relative numbers of galaxies predicted for the $q_o = 0.05$ evolutionary model, which appear to be in good agreement with the data, peaking at the colours corresponding to $z \approx 2$.

Figure 4c.
As Fig. 4b with the contours here representing the relative numbers of galaxies predicted for the $q_o = 0.5$ ‘disappearing dwarf’ (dE) model, which again appear to be in reasonable agreement with the data.

**Figure 4d.**

As Fig. 4b with the contours here representing the relative numbers of galaxies predicted for the $q_o = 0.5$ low redshift dwarf (dSp) model. The data show that this model is inappropriate, as it clearly predicts too many low redshift, $z \approx 0.5$, spiral galaxies.
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