The K-band luminosity function at $z = 1$: a powerful constraint on galaxy formation theory

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Abstract

There are two major approaches to modelling galaxy evolution. The “traditional” view is that the most massive galaxies were assembled early and have evolved with steeply declining star formation rates since a redshift of 2 or higher. According to hierarchical theories, massive galaxies were assembled much more recently from mergers of smaller subunits. Here we present a simple observational test designed to differentiate between the two. The observed K-band flux from a galaxy is a good measure of its stellar mass even at high redshift. It is likely only weakly affected by dust extinction. We compute the evolution of the observed K-band luminosity function for traditional, pure luminosity evolution (PLE) models and for hierarchical models. At $z = 0$, both models can fit the observed local K-band luminosity function. By redshift 1, they differ greatly in the predicted abundance of bright galaxies. We calculate the redshift distributions of K-band selected galaxies and compare these with available data. We show that the number of $K < 19$ galaxies with redshifts greater than 1 is well below the numbers predicted by the PLE models. In the Songaila et al (1994) redshift sample of 118 galaxies with $16 < K < 18$, 33 galaxies are predicted to lie at $z > 1$. Only 2 are observed. In the Cowie et al (1996) redshift sample of 52 galaxies with $18 < K < 19$, 28 galaxies are predicted to lie at $z > 1$. Only 5 are observed. Both these samples are more than 90% complete. We conclude that there is already strong evidence that the abundance of massive galaxies at $z \sim 1$ is well below the local value. This is inconsistent with the traditional model (unless most massive galaxies are extremely heavily obscured by dust at redshift 1), but similar to the expectations of hierarchical models.

Keywords: galaxies:formation, evolution; galaxies: stellar content
1 Introduction

At present there are two main approaches to modelling galaxy evolution. The “traditional” view is that the most massive galaxies – the big ellipticals, S0s and early-type spirals – formed first and have been evolving with strongly declining star formation rates since at least a redshift of 2. The less massive late-type spiral and irregular galaxies formed their stars at a roughly constant rate over a Hubble time and in many cases undergo substantial bursts. Alternatively, according to hierarchical theories of galaxy formation, massive galaxies were assembled recently from mergers of smaller subunits.

Traditional models adopt a simple “backwards-in-time” technique for calculating how the observed properties of galaxies evolve as a function of redshift (e.g. Tinsley 1980; Bruzual & Kron 1980; Koo 1981; Shanks et al 1984; King & Ellis 1985; Yoshii & Takahara 1988; Guiderdoni & Rocca-Volmerange 1990). The two basic inputs are a) the observed present-day luminosity function divided by morphological type, and b) a parametrization of the mean star formation rate history of galaxies of a given morphological type. These star formation histories are tuned to reproduce the spectral energy distributions of nearby spirals and ellipticals. It is usually assumed that all galaxies form at the same redshift and evolve as closed box systems. Stellar population synthesis models are used to compute how the galaxy luminosity function evolves as a function of lookback time, and predictions are then made for the counts, redshift distributions and colours of faint galaxies.

Hierarchical models of galaxy formation follow the formation and evolution of galaxies within a merging hierarchy of dark matter halos (e.g. White & Rees 1978; White & Frenk 1991; Lacey et al 1993; Kauffmann, White & Guiderdoni 1993; Cole et al. 1994; Somerville 1997). An analytic formalism allows the progenitors of a present-day object, such as a cluster, to be traced back to arbitrarily early times. Simple prescriptions are adopted to describe gas cooling, star formation, supernova feedback and the merging of galaxies. Finally, stellar population synthesis models are used to generate luminosity functions, counts and redshift distributions for comparison with observations.

There have been many recent papers claiming that either the traditional models or the hierarchical models can provide good fits to available data on high redshift galaxies. Most of the recent papers discussing traditional models invoke a local luminosity function with a “steep” (α < −1) faint-end slope in order to reproduce the observed high number density of faint blue galaxies. Dust extinction is also included to avoid overproducing blue, star-forming galaxies at high redshift (Gronwall & Koo 1995; Campos & Shanks 1997; Pozzetti et al 1996). The hierarchical models predict a local luminosity function with a steep faint-end slope (perhaps too steep) and hence have little trouble in matching the counts. Because bright galaxies have not yet formed at high redshift, the hierarchical models can reproduce the redshift distributions without requiring dust (Kauffmann, Guiderdoni & White 1994; Cole et al 1994; Heyl et al 1995; Baugh, Cole & Frenk 1996).

In this Letter, we present an observational test that is designed to differentiate between the traditional and hierarchical scenarios. To do this, we concentrate on the aspect that differs the most between the two pictures – the redshift evolution of the most massive galaxies. We show that the observed K-band flux from a galaxy provides a good measurement of its total stellar mass out to redshifts in excess of 2 for all but the most extreme starbursting systems. Moreover, the K-band is only weakly affected by extinction at these redshifts. We compute the
evolution of the observed K-band luminosity function for traditional and hierarchical models, assuming both high-density ($\Omega = 1$) and low-density ($\Omega = 0.2$) cosmologies. We use the new population synthesis models of Bruzual and Charlot (in preparation), which include updated stellar evolutionary tracks and new spectral libraries. At $z = 0$, both the traditional models and the $\Omega = 1$ hierarchical model can give a good fit to the local K-band luminosity functions of Gardner et al (1997) and Szokoly et al (1998). By redshift 1, the two give very different predictions for bright galaxies. At $z = 1$, the traditional models predict 10 times more galaxies with $K < 17$ than do the hierarchical models. At $z = 2$, the traditional models predict fifty times more galaxies with $K < 19$.

We then calculate the redshift distributions of galaxies with $K < 19$ and compare these with the Hawaii Deep Field Samples of Songaila et al (1994) and Cowie et al. (1996). We show that the observed number of bright galaxies with redshifts greater than 1 is well below the number predicted by the traditional models. In the Songaila et al (1994) sample of 118 galaxies with $16 < K < 18$, 33 galaxies are predicted to lie at $z > 1$. Only 2 are observed. In the Cowie et al (1996) sample of 52 galaxies with $18 < K < 19$, 28 are predicted to lie at $z > 1$. Only 5 are observed. Both these samples are more than 90% complete.

We conclude that there is already strong evidence that the abundance of massive galaxies has declined substantially at $z \sim 1$. This is inconsistent with the traditional models, unless most massive galaxies are extremely heavily obscured by dust at this redshift, but similar to the expectations of hierarchical models.

2 Relating observed K-magnitudes to stellar mass

In figure 1, we show the observed K-magnitude of a galaxy with $10^{11} M_\odot$ of stars as a function of its observed redshift. We assume $q_0 = 0.5$, $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. (Note that this is not an evolutionary plot for any specific galaxy. Rather it shows the apparent brightness of a galaxy which has $10^{11} M_\odot$ of stars at the redshift when it is observed.) The three different curves in the plot are for three possible star formation histories of the galaxy. The solid line shows the predicted K-band magnitude of the galaxy if all its stars formed in a burst at $z = \infty$. The short-dashed line shows the K-magnitude if the galaxy formed its stars at a constant rate from $z = \infty$ to the redshift of observation. The long-dashed line is for a galaxy that formed 80% of its stars at a constant rate, and 20% over the $10^8$ years immediately before it is observed. This is supposed to represent a galaxy that is undergoing a strong starburst. In the lower panel of figure 1, we plot the observed $B - K$ colours for the same three star formation models. Note that we have adopted a Scalo IMF with upper and lower mass cutoffs of $100 M_\odot$ and $0.1 M_\odot$. A 10 Gyr single-age stellar population has a K-band mass-to-light ratio of $\sim 0.6$, in good agreement with the estimated K-band mass-to-light ratios of elliptical galaxies (Mobasher et al 1998).

Figure 1 shows that galaxies of the same stellar mass will have roughly the same observed K-magnitude, independent of their star formation histories. The difference in K-luminosity between the initial burst and constant star formation models is less than a factor 2. Even the starburst model differs from the initial burst model by less than a factor 3 at $z < 2$. This is in marked contrast to the observed B-band luminosities, which, for high redshift galaxies, are dominated by the flux from young massive stars. Differences in $B - K$ colour of up to 9
Figure 1: *Upper panel:* The apparent K-band magnitude of a galaxy with $10^{11} M_\odot$ of stars observed at redshift $z$. The solid line shows results if all stars form in a burst at $z = \infty$. The short-dashed line assumes constant star formation until the epoch of observation. The long-dashed line is a “starburst” model (see text). *Lower panel:* The observed B-K colours of these galaxies.

Magnitudes are obtained for different star formation models. From figure 1, one can also infer that evolution at $z < 2$ in the abundances of galaxies more massive than $10^{11} M_\odot$ should be evident even in relatively bright ($17 < K < 19$) K-selected samples.

3 The Models

3.1 The traditional models

The traditional or pure luminosity evolution (PLE) model we employ is similar to that described in Pozzetti et al. (1996). The present-day luminosity function is divided into a set of 4 Hubble types (E/S0, Sa-Sb, Sc-Sd, Sm-Im) using the results of Marzke et al (1994) on the relative abundances of galaxies of differing morphology in the CfA Redshift Survey. Because the Schechter-function $M^*$ derived for the CfA survey is considerably fainter than that found for other recent surveys covering a larger area, we have chosen to normalize the total $B$-band luminosity function using the Schechter function fits derived for the ESO Slice Project (ESP) redshift survey ($\alpha = -1.22, M_* = -19.61 + 5 \log h, \phi^* = 0.020 h^3 \text{Mpc}^{-3}$) (Zucca et al 1997). At the bright end, the ESP luminosity function agrees well with the luminosity functions derived for the Stromlo-APM and the Las Campanas redshift surveys (Loveday et al 1992; Lin et al 1996). We compute the spectral evolution of E/S0, Sa-Sb and Sc-Sd galaxies using Bruzual & Charlot (1998) models with exponentially declining star formation rates with star formation timescales of 1, 4 and 15 Gyr, respectively. For the adopted Scalo (1986) initial
mass function, solar metallicity and formation redshift $z_f = 5$, the models provide good fits to the spectral features and the colours of nearby galaxies of these types from the ultraviolet to the infrared (Table 1; Bruzual & Charlot 1998). Local Sm-Im galaxies are too blue to be fit by models with exponentially declining or even constant star formation rates, if we assume a formation redshift of 5. Instead, we have adopted a model with constant star formation rate seen at a fixed age of 1.4 Gyr. This model best reproduces the colours and spectral properties of the propotypical Sm-Im galaxy NGC 4449 (Table 1; Bruzual & Charlot 1998). Since Sm-Im galaxies contribute very little to the luminosity function at bright magnitudes, their treatment in the models does not affect our conclusions. Our results are affected by the evolutionary model we adopt for the luminous E/S0 and Sa-Sb galaxies. We note that the choice of a Scalo IMF is a conservative one, since this results in milder luminosity evolution than the Salpeter IMF, which has a higher fraction of massive stars (Pozzetti et al 1996). We have not attempted to include any metallicity evolution in the traditional models. This will also not affect our conclusions since massive galaxies, which have short star formation timescales, quickly reach solar metallicity.

3.2 The hierarchical models

Because of the simplified way in which they treat the many physical processes which play a role in galaxy formation, hierarchical models have considerably more freedom than the traditional models. On the other hand the properties of the present galaxy population, which are used as an input in the traditional approach, are an output of the hierarchical models and so can be used to test them. As examples of hierarchical models, we here use a model from our earlier paper on the systematics of elliptical galaxies together with a low density variant. The reader is referred to Kauffmann & White (1993), Kauffmann, White & Guiderdoni (1993) and Kauffmann & Charlot (1998) for more details of our semi-analytic techniques for modelling the formation and evolution of galaxies in a hierarchical Universe. In the current paper we explore two possibilities:

1. An $\Omega = 1$ “standard” CDM model with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\sigma_8 = 0.67$, and $\Gamma = 0.5$. The star formation and feedback parameters are the same as in model A of Kauffmann & Charlot (1998), which was shown to provide a good fit to the slope and scatter of the colour-magnitude relation of elliptical galaxies in clusters. This model includes a prescription for chemical evolution and makes use of the metallicity-dependent spectral synthesis models of Bruzual & Charlot (1998).

2. An $\Omega = 0.2$ ($\Lambda = 0$) CDM model with $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\sigma_8 = 1$. Chemical evolution is also included in this model.

3.3 The present-day $K$-band luminosity function

Redshift zero $K$-band luminosity functions for the traditional and hierarchical models are shown as thick lines in figure 2. The Schechter function fit obtained by Szokoly et al (1998) for a sample of 175 galaxies to $K=16.5$ is shown as a dotted line on the plot. The fit obtained by Gardner et al (1997) for a wide-angle survey of 567 galaxies limited at $K=15$, is shown
as a thin dashed-dotted line. The traditional model and the $\Omega = 1$ CDM model both fit the observed local $K$-band luminosity function well, particularly at the bright end.

Note that in the traditional model, the $K$-band luminosity function is computed from the observed $B$-band luminosity function and the model $B - K$ colors corresponding to the different morphological types. The fact that the $K$-band luminosity function agrees well with the data gives us confidence that the the assumptions made in §3.1 are giving self-consistent results.

The $\Omega = 0.2$ CDM model fails to produce enough galaxies at $M^*$ by almost an order of magnitude. This failure of low-density models has been noted before (Kauffmann, White & Guiderdoni 1993). Baugh et al (1998) fit the number density of galaxies at the “knee” of the luminosity function in a low-density ($\Omega = 0.3, \Lambda = 0.7$) CDM model by adopting a brighter normalization, but they then vastly overproduce galaxies at the bright end of the luminosity function. (Basically, this is equivalent to shifting our curve to the right). Because of the failure of low-density hierarchical models to reproduce the shape of the local $K$-band luminosity function, we will not pursue their predictions any further in this Letter.

3.4 Evolution of the $K$-Band luminosity function

The predicted evolution of the observed differential $K$-band luminosity function is shown in figure 3. The solid and dotted lines show results from the traditional models, for $q_0 = 0.5$ and $q_0 = 0.1$ respectively. The dashed line shows results from the $\Omega = 1$ CDM model. All models assume $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$.

By $z = 1$, the predictions of the traditional and the hierarchical models deviate strongly at the bright end of the luminosity function. This just reflects the fact that in the hierarchical models, the most massive galaxies are still forming today. In the traditional models, the massive galaxies were already in place at $z = 1$ and were significantly brighter than at present because their stars were less evolved.

4 Comparison with data – the redshift distributions of $K$-selected galaxies

Complete $K$-selected redshift surveys of faint galaxies are not yet large enough to construct accurate luminosity functions at a series of redshifts. The young bright galaxies predicted by the traditional models should, however, show up as a “tail” of high redshift galaxies in these samples. In the $B$-band, the presence of high-$z$ tails in the predicted redshift distributions has been shown to depend sensitively on whether dust extinction is included in the modelling (Gronwall & Koo 1995; Campos & Shanks 1997). In the $K$-band, the effects of dust are not likely to be as significant.

In figure 4, we plot the cumulative fraction of galaxies with redshifts greater than $z$ for samples limited at $K=18, 19$ and $21$. The solid and dotted line show results for the $q_0 = 0.5$ and $q_0 = 0.1$ PLE models. The dashed line is the hierarchical model. The thin solid lines in figure 4 show recent observational results. The curve in the top panel is computed using the sample of Songaila et al (1994) and the curve in the middle panel is derived from the Hawaii Deep Field sample of Cowie et al (1996). In both cases, we have chosen conservative
Figure 2: The present-day $K$-band luminosity function of models (thick lines) compared with the data (thin lines). The short-dashed line is the $\Omega = 1$ hierarchical model, the dashed-dotted line is the $\Omega = 0.2$ hierarchical model and the solid line is the PLE model. The dotted line is the Schechter fit derived by Szokoly et al (1998). The thin dashed-dotted line is the fit obtained by Gardner et al (1997).
Figure 3: The evolution of the observed differential $K$-band luminosity function of galaxies. Solid and dotted lines show the $q_0 = 0.5$ and $q_0 = 0.1$ PLE models. The dashed line is the hierarchical model.
limiting magnitudes in order to ensure that the redshift data are nearly complete (> 90% in both cases) and that the derived redshift distributions are not biased by selection effects. There are 118 galaxies with $16 < K < 18$ in the Songaila redshift sample and 52 galaxies with $18 < K < 19$ in the Cowie redshift sample. In the plot, we do not include galaxies without known redshifts (11 galaxies in Songaila et al. and 4 galaxies in Cowie et al.)

It should be noted that all the models produce roughly the right total number of galaxies per unit area on the sky to $K = 21$. The $q_0 = 0.5$ PLE model fits the counts extremely well to $K=21$. The $q_0 = 0.1$ model counts are a factor of two too high at $K=21$, because of the increased volume at high redshift in a low-density cosmology. The hierarchical model counts are also a factor 2-3 too high at this magnitude, because the faint end of the $K$-band luminosity function is too steep in this model (see figure 2). This accentuates the tendency for the hierarchical redshift distributions to be dominated by faint, low-z galaxies.

Figure 4 shows that the fraction of galaxies predicted to lie at high redshift is very much larger in the PLE models than in the hierarchical model. It is also apparent that the number of galaxies observed at redshifts greater than $z \approx 0.5$ falls well below the predictions of the PLE models in both the Songaila and the Cowie data samples. For the $16 < K < 18$ sample, the PLE models predict that 33 galaxies should have been detected at $z > 1$, when in fact only 2 such galaxies are found. A KS test gives the probability that the Songaila sample is consistent with the PLE redshift distribution as less than $10^{-4}$, even if all the galaxies without redshifts are arbitrarily assigned to $z > 4$. A similar result is obtained for the Cowie et al. sample. This shows that our conclusions are not being affected by finite sample statistics. In anticipation of future redshift surveys complete to even fainter limiting magnitudes, we show the predicted redshift distributions for galaxies with $19 < K < 21$ in the bottom panel of figure 4.

Finally, we note that similar results have been found by others. Pozzetti et al (1996) show that their PLE models fail to match the Songaila et al. (1994) redshift distributions. Cowie et al (1996) note that the median redshift of their sample as a function of observed K magnitude falls below the predictions of models with mild luminosity evolution. In our analysis, we focus our attention on the evolution of the bright end of the $K$-band luminosity function, since this where the predictions of the traditional and the hierarchical models diverge most strongly.

5 Discussion and Conclusions

In previous work we showed that the abundance of galaxies with colours consistent with passively evolving early-type galaxies was a factor 2-3 lower at a redshift of 1 than at present (Kauffmann, Charlot & White 1996; see also Zepf 1997). It was not clear from our analysis whether this was because present-day ellipticals were forming stars at high redshift and were thus not as red as specified by simple passive evolution models, or because many ellipticals had simply not yet assembled by $z = 1$.

The analysis presented in this Letter is considerably more general in that it applies to the evolution of the entire population of massive galaxies. From our comparison of the data with the models, we conclude that the abundance of massive galaxies is substantially below its present value at $z = 1$, in contradiction with the traditional picture of galaxy formation. If massive galaxies were forming stars more rapidly than we have assumed at high redshift,
Figure 4: The redshift distributions of galaxies selected according to $K$-magnitude. Solid and dotted lines show the $q_0 = 0.5$ and $q_0 = 0.1$ PLE models. The dashed line is the hierarchical model. The thin solid line is derived from the Songaila et al (1994) sample in the upper panel and from the Cowie et al (1996) sample in the middle panel.
they would appear even brighter at $K$, and the failure of the traditional picture would be even more significant. The only remaining “escape route” would be for a large fraction of today’s massive galaxies to be so heavily obscured by dust at $z = 1$, that even the observed $K$-band is significantly affected (Franceschini et al 1997). This does not seem likely to us, because damped Lyman-alpha systems, which are good probes of the conditions within high column density gas clouds, contain rather little dust at $z \approx 2$ (Pei, Fall & Bechtold 1991; Pettini et al. 1997)

We suggest that massive galaxies have continued forming until recent times through a process of merging and accretion, as predicted by hierarchical theories of galaxy formation. Future wide-area $K$-selected redshift surveys will enable this buildup of galaxies to be quantified more accurately.

Acknowledgments
We thank Simon White for helpful discussions. This work was carried out under the auspices of EARA, a European Association for Research in Astronomy, and the TMR Network on Galaxy Formation and Evolution funded by the European Commission.
Table 1: Star formation laws and predicted colours of different Hubble types

| Type   | SFR            | B-V (z=0) | V-K (z=0) |
|--------|----------------|-----------|-----------|
| E/S0   | exp, $\tau = 1$ | 0.97      | 3.22      |
| Sa/Sb  | exp, $\tau = 4$ | 0.83      | 3.00      |
| Sc/Sd  | exp, $\tau = 15$ | 0.61      | 2.75      |
| Sm/Im  | const, age=1.4 | 0.28      | 2.00      |
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