GALAXY EVOLUTION FROM DEEP GALAXY COUNTS

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Abstract. We present deep galaxy number counts and colours of $K-$band selected galaxy surveys. We argue that primeval galaxies are present within the survey data, but have remained unidentified. There are few objects with the colours of an L^* elliptical galaxy at a redshift of $z \approx 1$, in contradiction to standard luminosity evolution models. We present $K-$band photometry of the objects in a spectroscopic redshift survey selected at $21 < B < 22.5$. The absolute K magnitudes of the galaxies are consistent with the no-evolution or pure luminosity evolution models. The excess faint blue galaxies seen in the $B-$band number counts at intermediate magnitudes are a result of a low normalization, and do not dominate the population until $B \approx 25$. Extreme merging or excess dwarf models are not needed at $z < 1$.

1. Introduction

Galaxy number counts and the colours of the field galaxies making up those counts have proven to be a powerful tool for investigating galaxy evolution and the cosmological geometry. Observations made at a wide range of magnitudes and wavelengths can, in principle, distinguish between different evolutionary and cosmological models. Studies of galaxy evolution are statistical in nature, and field galaxies avoid the short-timescale effects associated with radio galaxies and quasars which make their selection function difficult to determine. Similarly, galaxies in clusters may show environmental effects. Optical galaxy surveys at bright magnitudes have covered very large areas by scanning photographic plates (Maddox *et al.*, 1990). Long exposures with CCDs have reached $B = 28$, (Metcalfe *et al.*, 1994) while

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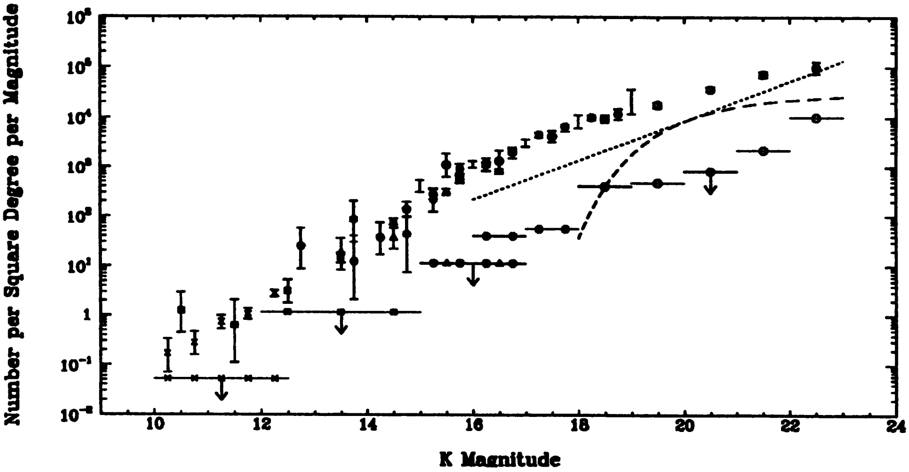

Figure 1. Primeval galaxy non-detection limits; The K—band number counts from Gardner *et al.* (1993), plotted with a simple model for primeval galaxies. The dotted line provides a locus along which a suitable luminosity function, the dashed line, will slide. Also plotted are the upper limits on the density of objects which could be identified, but are not detected, for each of the surveys. Since the primeval galaxy model is above the upper limits on undetected objects, it is likely that primeval galaxies are hiding within the survey catalogs, but have the same colours as normal galaxies, and remain unidentified.

spectroscopic redshift surveys to the current limit of $B < 24$ (Cowie *et al.*, 1991) have placed limits on the models of evolution proposed to explain the counts.

The near-infrared, or K band, provides several advantages for faint galaxy studies, including smooth K—corrections and well-understood luminosity evolution. The K band represents the reddest we can observe from the ground without the very high backgrounds of the thermal infrared. The flux is dominated by long-lived near-solar mass stars which are comparable in lifetime and timescales of evolution to the age of the galaxy. These stars make up the bulk of the galaxy, and the absolute K magnitude is a measure of the mass of light matter in a galaxy.

2. Primeval Galaxies and the Number Counts

Much early near-infrared survey work was motivated by a theoretical model of dust-free protogalaxies developed by Partridge and Peebles (1967; PP). In this model, galaxies form through the collapse of overdense regions, pass through a very luminous phase in which the majority of the stars are formed, and appear as large, bright objects at $10 < z < 100$, with Lyman α redshifted beyond the optical.

It is interesting to consider the large red primeval galaxy model of PP in light of the current K−band number counts. Early researchers often used a very optimistic set of assumptions to justify conducting surveys using the limited technology available at the time. Lilly and Cowey (1987), however, constructed a model which is fairly independent of assumptions of cosmological geometry and timescale of star formation by assuming that a primeval galaxy will have the flat spectrum ($f_\nu \propto \nu^{-1}$) characteristic of an unreddened young stellar population.

In the initial star-bursting phase of the PP model, the majority of the metals in the universe were produced, and this metal production by stellar nucleosynthesis would have produced a surface brightness on the sky dependent only on the mass fraction of metals, the density of matter processed to produce the metals, and the redshift of galaxy formation. Assuming that the primeval galaxies have a flat spectrum, the K−band surface brightness is independent of z_{form} unless $z_{form} > 20$ and Lyman α has passed out of the K band. This surface brightness defines a line on the number count diagram along which an appropriate luminosity function would slide, depending upon the specifics of the model, such as z_{form}, the cosmological geometry, and the duration of the starbursting phase. Geometry then gives the number density of the progenitors of objects with a given present density. Fig. 1 is the K−band galaxy number counts, from Gardner *et al.* (1993), with this model plotted.

In this model, the predicted number of primeval galaxies is lower than the number of normal galaxies for $K > 20$, and so a very important consideration is whether we can recognize them for what they are. In the surveys discussed in this paper, there are no large ultrared objects of the kind predicted by PP to be primeval galaxies at high redshifts ($z > 7$). If we assume that this failure to find primeval galaxies means that they are not there (i.e., if we assume primeval galaxies would not be confused with normal galaxies or stars), then we have placed a much stronger constraint on the model. Plotted in Fig. 1 are the upper limits implied by the failure to identify primeval galaxies in the area covered at each magnitude bin.

Fig. 1 shows that a simple model of the surface brightness on the sky of metal formation predicts number counts of primeval galaxies which are below the observations of normal galaxies, but above the limits of detection in the current surveys. While these surveys contain no unambiguous detections of primeval galaxies, this figure says that primeval galaxies are hiding as a minority population within the survey data.

There are a wide range of primeval galaxy models, predicting everything from bright extended red objects to faint compact blue ones. However, various observational programs, including this one, are beginning to put strong constraints on some of the models, and it appears likely that the field is close to making an unambiguous discovery of a population of primeval

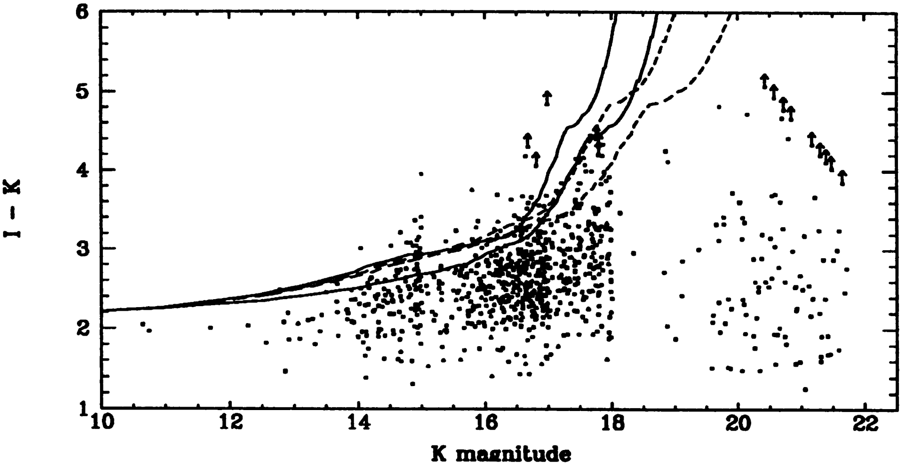

Figure 2. $I-K$ vs K from Gardner (1994). Also plotted are a model for a K^* elliptical galaxy. The dashed lines are the no-evolution model, with the lower line being for $q_0 = 0.5$, and the upper line being for $q_0 = 0.02$. The solid lines include Yoshii and Takahara (1988) evolution. Most galaxies at the bright end are elliptical and Sa galaxies at near K^*. At the faint end, however, the galaxies drop away from the lines, and there are very few galaxies with the colours of L^* ellipticals at $z > 1$.

galaxies. This will come either through the spectroscopic identification of a flat spectrum object at high redshift, or, more subtly, through statistical arguments about a moderately high redshift active star forming population.

3. Colour Data

The $K-$band number counts were presented by Gardner *et al.* (1993), and were discussed there in the context of the $B-$band counts and the median $B-K$ colour as a function of K magnitude. Fig. 2 is a plot of the $I-K$ colour as a function of K magnitude from Gardner (1994). Also plotted are a no-evolution model for an elliptical galaxy at K^*, for $q_0 = 0.02$ and $q_0 = 0.5$ ($\Lambda = 0$), and a model of this galaxy type with Yoshii and Takahara (1988; YT) luminosity evolution. The models are the reddest that galaxies can normally be expected to get, although the data does show some scatter around this line due to noise. The general trend of the $I-K$ colours of the galaxies is to follow the models for elliptical galaxies at the bright end. Photometric surveys of this type generally pick out the intrinsically brightest galaxies at each apparent magnitude, since they are the most distant, and therefore sample the largest volume. A $K-$band selected survey will pick out the reddest objects. Thus one expects, in K selected surveys, to be dominated by L^* elliptical and S0 galaxies, and this is evident in the data at the bright end. At the faint end, however, these L^* unevolved

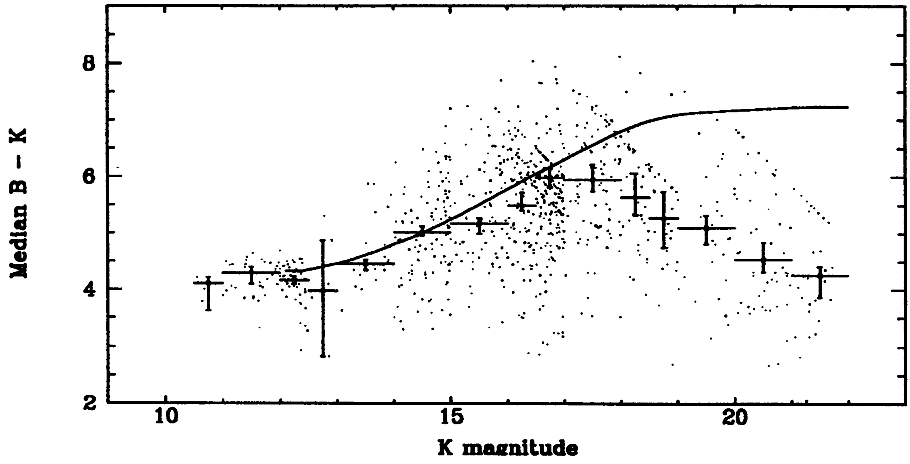

Figure 3. Median $B-K$ colour vs K from Gardner (1994). Also plotted is a no-evolution model. The data follow this model until $K > 17$ when the galaxies rapidly become much bluer than the no-evolution case.

elliptical galaxies are no longer seen. Essentially, objects with the colours of non-evolved L^* elliptical galaxies at a redshift of $z \approx 1$ do not appear in the data. YT evolution is not enough to explain this deficiency. With $z_{form} = 5$, the elliptical galaxies at $z \approx 1$ show little difference from the present day SED, and the K−corrections dominate the colours, making the galaxies very red. While a much lower redshift of galaxy formation might save this model, that would create other problems. The data say that there is much more star formation in the galaxy population at $z \approx 1$ than the standard luminosity evolution models predict.

This effect is also seen in Fig. 3, a plot of $B - K$ colour against K magnitude. At the bright end of this plot, the galaxies do not change in colour, as they are at too low redshift for the K−correction to change their colour. At about $K \approx 13$ the $B - K$ colour gets redder, because the K−correction begins to dominate the colours. The data is plotted against a no-evolution model of the median $B-K$ colour. In this magnitude range the no-evolution model is a good fit to the data, and the effects of evolution are neither expected to be nor seen to be large. However, beginning at $K \approx 17$, the no-evolution model is redder than the majority of the objects, and is no longer a good fit to the median colour. At the faintest levels observed, the $B - K$ colour rapidly gets bluer, dropping away from the no-evolution prediction.

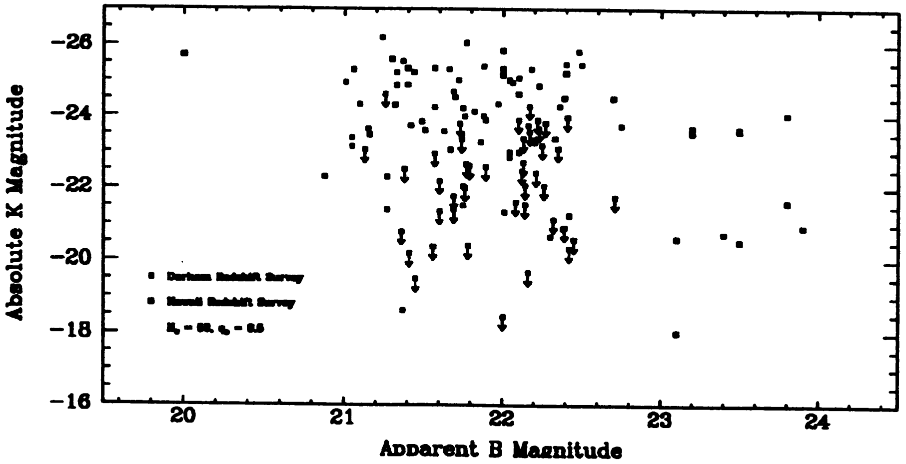

Figure 4. Absolute K magnitude plotted against apparent B magnitude for the Colless *et al.* (1990) and Cowie *et al.* (1991) samples.

4. K−band Photometry of Redshift Survey Objects

Much attention has been paid recently to an apparent excess of faint blue galaxies observed in photometric surveys. When the models of the B−band number counts are normalized at $B = 16$, the data show an excess over the luminosity evolution models of a factor of 2 at $B = 22$ (Tyson, 1988; Lilly *et al.*, 1991). However, the K−band number counts do not show this same excess (Gardner *et al.*, 1993). The shape of the number-redshift distribution of surveys conducted at $20 < B < 22.5$ by Broadhurst *et al.* (1988) and Colless *et al.* (1990) are fitted by the no-evolution model. The median redshifts of the data from these surveys, and deeper data of Cowie *et al.* (1991) and Allington-Smith *et al.* (1992) show no evolution as faint as $B = 24$. Proposed explanations for the high B−band number counts include massive amounts of merging at intermediate redshifts ($z \approx 0.4$) (Broadhurst *et al.*, 1992) and an excess population of dwarf galaxies which appears at these redshifts, but has dissipated or faded by the present epoch (Cowie *et al.*, 1991).

With the intent of investigating this population of excess faint blue galaxies, we obtained K−band photometry of the redshift survey objects of Colless *et al.* (1990, 1993), selected at $21 < B < 22.5$. This redshift survey observed 178 objects in six fields, achieving an identification rate of 81% overall, and 95.5% in selected regions. We have observed 106 of the 115 identified galaxies of this data set, and identified 63 at the 2σ level or greater. We wished to test the claim of Cowie *et al.* (1991) that the proportion of intrinsically low-mass galaxies, that is, galaxies with low

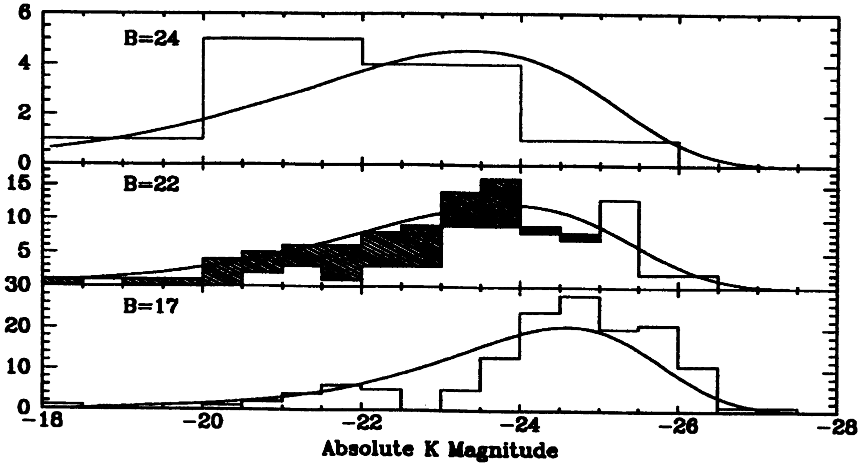

Figure 5. Histograms of the absolute K magnitude for 3 B−band selected samples, the Peterson *et al.* (1986) sample selected at $16 < B < 17$, the Colless *et al.* (1990) sample selected at $21 < B < 22.5$, and the Cowie *et al.* (1991) sample selected at $23 < B < 24$. The lines are no-evolution model predictions from the models of Yoshii and Takahara (1988). The shaded region in the $B = 22$ histogram represents galaxies undetected in K, which are plotted at their 2σ upper limits.

absolute K magnitude, increases with the depth of the sample.

While the small sample of Cowie *et al.* (1991), plotted in Fig. ?? along with the new data, was dominated by near K^* galaxies in the regions at $B < 23$, the new data show that there is a significant population of low mass galaxies in the brighter sample. Fig. ?? shows the histograms of three redshift surveys for which K−band photometry exists. At the bright end, $B < 17$, 3 fields of the DARS (Peterson *et al.*, 1986) redshift survey were observed by Mobasher *et al.* (1986), and as expected, the data is fit by the no-evolution model. At the faint end, the 11 identified galaxies of the Cowie *et al.* (1991) sample with $23 < B < 24$, show that the no-evolution prediction, based upon the model of Yoshii and Takahara (1988), nearly fits the data. There does appear to be an excess of dwarfs, but this effect is at the 1σ level, and a larger sample is needed to test this hypothesis.

The new data, while subject to the incompleteness of the 43 upper limits on the flux, is also fitted by the no-evolution model in Fig. ??. At these magnitude levels, pure luminosity evolution makes little difference in the model predictions, and the amount cannot be determined, but the effects of more extreme models such as merging or excess dwarfs are not evident in the data. Thus, in the region $20 < B < 22$, where the mean redshift is $z = 0.3$ (Colless *et al.*, 1990), the shape of the luminosity function of field galaxies is normal, both in the B band and in the K band.

At $B = 22$, the excess over the models seen in the $B-$band number counts is a factor of 2. The redshift distribution at this level, both in the $B-$ and the $K-$bands shows no sign that anything other than luminosity evolution is needed. The problem could reside in the normalization of the number counts. If the number count models are normalized at $B = 18$, rather than $B = 16$, then the counts at $B = 22$ are fitted by the pure luminosity evolution model, with no excess (Shanks, 1990). The $B = 16$ number counts are underdense, due to either large-scale structure on scales of 100 Mpc, or to systematics in the photographic magnitudes used to compile number counts at this bright level. Maddox *et al.* (1990) have proposed large amounts of luminosity evolution at very low redshift ($z <$ 0.1.) The effects of large-scale structure dominate the number counts at the brightest magnitudes, and these effects become less important with magnitude as larger volumes are sampled, until they are finally dominated by the Poisson errors. The study of the redshift distribution at the north and south galactic poles by Broadhurst *et al.* (1990) shows a periodicity in the distribution at 128 h^{-1} Mpc., of which we are approximately in the center. Structure of this size will dominate the number counts at $B = 16$, becoming less important at $B = 18$. With this higher normalization, the excess faint blue galaxies do not dominate the number counts until $B > 25$, where we do not know the redshifts of the galaxies.

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FERGUSON: One thing that field-galaxy K-band surveys give you that cluster surveys don't is the ability to test whether the co-moving density of elliptical galaxies is evolving. Is your impression from the data that this is the case? Can you give some specific numbers.

GARDNER: We do not have types for the galaxies in the surveys, only the colours, making this a difficult question to address quantitatively. We can say from the data that there are fewer galaxies than expected with the colours of ellipticals at $K > 18$, but we do not have the resolution to say anything about their morphology.

TAYLER: In your diagram showing possible primeval galaxies, how many might you expect to be present given the total number of galaxies in your survey?

GARDNER: The surface brightness produced by the primeval galaxies is relatively model-independent, but the magnitudes of the galaxies making up this surface brightness depends on the choice of various parameters, such as the redshift and timescale of formation, and the cosmological geometry. For reasonable values of these parameters, 1/3 of the 84 galaxies at $K = 21$ in our survey are primeval.