The History of Galaxies and Galaxy Number Counts

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ABSTRACT

A simple quantitative model is presented for the history of galaxies to explain galaxy number counts, redshift distributions and some other related observations. We first infer that irregular galaxies and the disks of spiral galaxies are young, probably formed at $z \approx 0.5 - 2$ from a simultaneous consideration of colours and gas content under a moderate assumption on the star formation history. Assuming that elliptical galaxies and bulges of spiral galaxies, both called spheroids in the discussion, had formed early in the universe, the resulting scenario is that spiral galaxies formed as intergalactic gas accreting onto pre-existing bulges mostly at $z \approx 1 - 2$; irregular galaxies as seen today formed by aggregation of clouds at $z \approx 0.5 - 1.5$. Taking the formation epochs thus estimated into account, we construct a model for the history of galaxies employing a stellar population synthesis model. We assume that the number of galaxies does not change except that some of them (irregulars) were newly born, and use a morphology-dependent local luminosity function to constrain the number of galaxies. We represent the galaxies by E/S0, Sab, Sc and Irr; low luminosity dwarfs or any objects unobservable today do not play a role in our considerations. In our model, spheroids follow passive evolution and the luminosity of spiral galaxies evolves only very slowly for a wide redshift interval due to a counterbalance between fading stars and new star formation from the gas replenished from intergalactic space. Irregular galaxies evolve moderately fast for $z < 1$. The predictions of the model are compared with the observation of galaxy number counts and redshift distributions for the $B$, $I$ and $K$ colour bands. We show that $K$ band observations are largely controlled by spheroids, which make them particularly suitable to study cosmology. We argue that $\Omega = 1$ models are disfavoured, unless the basic assumptions of the present model are abandoned. The $K$ band observations reach quite high redshift: for instance observations at $K=23$ mag may explore the formation epoch, which could be as high as $z > 5$. On the other hand, galaxies observed in the $B$ band are dominated by disks and irregulars, spheroids making a very small contribution. It is shown that young irregular galaxies cause the steep slope of the counts. The fraction of irregular galaxies increases with decreasing brightness: at $B = 24$ mag, they contribute as much as spiral galaxies. Thus, “the faint blue galaxy problem” is solved by invoking young galaxies. This interpretation is corroborated by a comparison of our prediction with the morphologically-classified galaxy counts in the $I$ band. We do not invoke
sporadic star bursting: star formation takes place steadily as does today, but galaxies (especially irregulars) are gaseous at higher redshift, and hence star formation is much more active than today. Consistency is also shown with the constraint on the luminosity evolution from a Mg II quasar-absorption-line selected sample. We estimate that 2/3 of the baryons in stars are stored in spheroids and 1/3 in disks, only < 10% being in irregular galaxies. The amount of baryons in disk stars is increasing, as they form to $\Omega_b \sim 0.001$, which just offsets the decrease of neutral gas towards the present epoch, as inferred from quasar absorption line surveys.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: fundamental parameters
1. Introduction

When galaxies formed and how they evolved are among the central issues of cosmology today. The traditional clue to this problem has been provided by the number count of galaxies as a function of apparent magnitude. Early observations in the blue band showed that the number of galaxies per unit angular area increases faster than is expected in simple models for fainter magnitude (Koo & Kron 1992, for a review). It has become clear, however, that the number count alone does not allow an unambiguous interpretation. Over the last decade, much effort has been expended to obtain redshift of faint galaxies (Broadhurst, Ellis & Shanks 1988, hereafter BES; Colless et al. 1990; 1993; Lilly, Cowie & Gardner 1991; Koo & Kron 1992; Songaila et al. 1994; Glazebrook et al. 1995a; Lilly et al. 1995; Ellis et al. 1996). These redshift surveys have revealed, when combined with the count data, that the distribution of galaxies in the universe is much more puzzling than it looked: the excessive number of galaxies observed in the number count seemed to be most simply explained by assuming luminosity evolution of galaxies (e.g., Koo & Kron 1992), but the redshift surveys have indicated that the shape of the redshift distribution appears almost as is predicted with a no-evolution model, with the normalization, however, being larger by a factor of two. Simple models with all galaxies undergoing substantial luminosity evolution, which account for the steep slope of the number count, predict too many galaxies having high redshift to be consistent with the observations (e.g., Ellis 1990; Lilly 1993) (though this seems to have been somewhat overstated).

There have been a number of attempts to solve this problem: some authors speculated that the excess count is due to a new population of galaxies which have undergone star burst at rather low redshift (BES; Cowie, Songaila and Hu 1991). Babul & Rees (1992) and Babul & Ferguson (1996) interpreted this new population as dwarf galaxies from collapsed Lyman α clouds, eventually faded into galaxies making up an invisible population. Some other authors have assumed a heuristic morphology-dependent luminosity evolution so that subluminous galaxies evolve fast to explain high counts while keeping the shape of redshift distribution as is in the no-evolution model, rather than introducing a new population (BES; Lilly 1993; Phillips & Driver 1995). Another class of explanation invokes mergers of galaxies with a very high merging rate (Guiderdoni & Rocca-Volmerange 1991; Broadhurst, Ellis & Glazebrook 1992; Carlberg 1992). The required rate to explain the steep slope of the B band count is so high that a typical galaxy gains 50% of mass over the past 5 Gyr. More recently, Gronwall & Koo (1995) suggested that the presence of an abundant non-evolving very blue dwarf population accounts for both counts and redshift data, although the meaning of this blue population is not clear to us.

Observational data have now accumulated for both counts and redshifts over a wide range of colours from B to near infrared K band, and the deepest redshift reaches beyond $z = 1$ (Glazebrook et al. 1995a; Songaila et al. 1994; Lilly et al. 1995). A large number of redshifts contained in the survey have enabled a direct construction of the $B$ band luminosity function as a function of redshift (Lilly et al. 1995; Ellis et al. 1996; see also Eales 1993). This prompts us to think that we already have enough data to understand the evolution of galaxies below $z \sim 1$. In addition, more varieties of clues have become available to understand the nature of faint galaxies. Sharp images of galaxies obtained with the HST have enabled a study of morphology to $I=24$ mag, giving us a direct probe concerning how the faint galaxies look like (Driver, Windhorst & Griffiths 1995; Glazebrook et al. 1995b; Abraham et al. 1996; Driver et al. 1996). The work has shown that the fraction of irregular galaxies increases sharply with magnitude beyond $I > 18 – 20$ mag. The same observations indicate that giant galaxies evolve only slowly, although they do indicate some evolution in colour, brightness and the detail of morphology. Another piece of evidence that giant galaxies evolve only slowly, if at all, comes from a Mg II quasar-absorption-line selected sample (Steidel, Dickinson & Persson 1994). The luminosity of galaxies that yield Mg II absorption lines for a quasar in their vicinity is remarkably constant both in the rest-frame $B$ and $K$ bands from $z = 0.3$ to $\approx 1$.

There are also a number of observations that tell us about the content of galaxies. The information that would directly constrain the model for evolution of galaxies is the estimate of the global star formation rate at $z = 0$ (Gallego et al. 1995) and high $z$ (Cowie, Hu & Songaila 1995; see also Madau et al. 1996 for a more recent work) from the strength of H$\alpha$ or [O II]$\lambda 3727$ emission lines. This quantifies the inference from early observations concerning the increase of star formation activity in the past (BES).
Yet another useful information is given by the measurement of the neutral hydrogen abundance in the universe as a function of redshift (Lanzetta, Wolfe & Turnshek 1995; Storrie-Lombardi, McMahon & Irwin 1996). The data show clear depletion of HI gas with time, suggesting that this gas has been used for star formation. This information can be utilized to constrain the total volume emissivity of galaxies (see, Pei & Fall 1995), on which direct information is also available from galaxy observations (Lilly et al. 1996).

From accumulating observations we now have a reasonable picture for the evolution of galaxies (Fukugita, Hogan & Peebles 1996): giant galaxies were already mature at $z \sim 1$ and evolve only slowly lower than this redshift, whereas subluminous galaxies evolve rapidly in the same redshift range. The latter are probably young galaxies formed close to $z \sim 1$. It has also been speculated that most of elliptical galaxies and bulges of the spiral galaxies, which altogether we call spheroids, formed before $z \gtrsim 3$, and spiral disks were assembled in the redshift range from $z \sim 3$ to 1.

In this paper we present a simple but quantitative model for the history of galaxies, which is broadly consistent with the observations. The model employs a population synthesis model of stars. In the traditional attempts, galaxies are assumed to have fully assembled at an early epoch of the universe (Searle, Sargent & Bagnuolo 1973; Sandage 1986; Yoshii & Takahara 1988), and the star formation rates are adjusted to reproduce galaxy colours today. In our attempt it is crucial to properly build in the epoch of the formation of galaxies in the stellar population synthesis model. For this purpose we first show that one can estimate the age of the galaxies as seen today from a simultaneous consideration of the colour and gas content of galaxies with the aid of moderate assumptions on the star formation history, and infer the age of irregular galaxies and also of disks of spiral galaxies. For elliptical galaxies, and also bulges of spiral galaxies from family resemblance (both are called spheroids), we adopt the conventional view that they formed at high $z$ as argued by Eggen, Lynden-Bell and Sandage (1962). We assume that the number of galaxies is conserved since they were born, and it is constrained by the local type-dependent luminosity function. We calculate the evolution of bulges and disks separately and assume delayed formation of disks and irregular galaxies. The spheroids are supposed to follow the passive evolution to now. Galaxies are grouped into four morphology types: E/S0, Sab, Sc, and Sdm-Irr which is simply referred to as Irr in this paper; low luminosity dwarf galaxies do not play an essential role in our argument. The mix of morphological types of galaxies is not constant, but depends on absolute luminosity.

The predictions of this model are compared with the observation of the galaxy number count and the redshift distribution in $B$, $I$ and $K$ bands. We do not discuss the $U$ band count, since we cannot model reliable $K$- and $E$-corrections for this band, and $U$ band data are too sensitive to the detail of galaxy activity. We discuss the evolution of gas and star content of galaxies predicted in the model. Through these comparisons with the observations we may conclude that the present model is reasonably well constrained for $z \lesssim 1 - 1.5$. The prediction for $z > 1.5$, however, is basically an extrapolation, and ill-constrained. A number of checkpoints are also discussed to prove or disprove the validity of the model and, more importantly, underlying assumptions taken in this paper.

We do not consider the no-evolution model seriously, since it is clearly unphysical. We know that elliptical galaxies must evolve even in the absence of new star formation after the burst, since the stars in the main sequence branch continuously evolve to giants, and the total luminosity should decrease with time (Tinsley 1972). This basic feature is a solid prediction of the stellar population synthesis model, although quantitative details depend on models, in particular on assumed initial mass functions. For spiral galaxies, there are more uncertainties: our model corresponds to the case where luminosity changes very little with time: the decrease of light due to evolution of stars is compensated by newly born stars formed from the gas replenished into the disk.

We note that the present model is quite different from “CDM cosmologies”, where morphologies of galaxies change from time to time due to mergers down to low redshift (Kauffmann, Guiderdoni & White 1994; Cole et al. 1994). That is, elliptical galaxies are not quite old, but formed by collision of, for instance, two spiral galaxies at rather low redshift (Toomre 1977).

One of the original reasons for interest in faint galaxy counts is that it may offer a chance to test world geometry (Sandage 1961). A number of attempts have been made aiming at this goal (e.g., Yoshii & Takahara 1988; Fukugita et al. 1990; Gardner, Cowie & Wainscoat 1993; Gronwall & Koo 1995). The reliability of the results, however, is strongly af-
2. Age and star formation rate of galaxies

2.1. Irregular galaxies

The two fundamental parameters that control the evolution of the stellar population are the age of the galaxy \( t_G \) and the star formation rate \( Q \left( \text{Gyr}^{-1} \right) \), provided that the initial mass function is fixed. We can obtain useful information concerning these parameters by plotting galaxies in the two dimensional plane, integrated galaxy colour versus gas. In Fig. 1 we show a diagram for irregular galaxies plotted in \( B-V \) versus \( \log M_{\text{gas}}/L_B \), where \( M_{\text{gas}} \) is mass of the neutral atomic gas estimated from the integrated 21cm HI flux, corrected for helium abundance of 25% in mass, with the aid of the formula given in the *Third Reference Catalogue of Bright Galaxies* (de Vaucouleurs et al. 1991, hereafter RC3). Molecular hydrogen is ignored. The data are taken from Buta et al. (1994), but a very similar figure can be obtained using the data given in RC3. The bars indicate one standard deviation of the distribution.

Evolutionary tracks are presented in the figure for a given \( Q \) using a conventional evolution model of galaxies, where star formation is assumed to take place at a constant rate against gas mass. For the present calculation, we adopt the closed model of Arimoto & Yoshii (1986), but other models also yield similar results. The track represented by a solid line corresponds to \( Q = 0.2 \left( \text{Gyr}^{-1} \right) \), which is the star formation rate in the solar neighbourhood, and is also consistent with the estimate for Sb-Sbc galaxies (Roberts 1963; Smith, Biermann & Mezger 1978; Kennicutt 1983; Sandage 1986). The ticks on the track indicate the age of galaxies, 1, 5, 10 and 15 Gyr after star formation began, so that dashed curves represent isochronal contours. We note that the traditional model, where irregular galaxies formed as old as the universe, assumes a very low \( Q \left( Q \approx 0.002 \left( \text{Gyr}^{-1} \right) \right. \), say) in order to obtain their blue colour \((B-V \approx 0.4)\). This terminating point of the \( Q = 0.002 \left( \text{Gyr}^{-1} \right) \) is indicated by an open circle. The family of evolutionary tracks indicates that one can obtain the same colour with a larger \( Q \) if the age of galaxies is younger; the gas fraction determines the age. The data point for irregular galaxies shows that they are as young as \( t_G = 3-10 \text{ Gyr} \) and \( Q \approx 0.1 - 0.2 \left( \text{Gyr}^{-1} \right) \), which is close to the solar neighbourhood value. The prediction of the traditional model, as presented by the open circle, is clearly inconsistent with the observation. We emphasize the large “error bars”, which indicate that...
the irregular galaxies observed today have not had a coeval formation at all, with an age spread of well over 4 to 12 Gyr.

One attractive feature with a larger $Q$, which is consistent with the value for spiral galaxies, is that it supports the validity of the Schmidt law, which states that the star formation rate is proportional to the HI gas amount to some power (Schmidt 1959). The approximate validity of the Schmidt law with power law index close to unity is supported by an analysis of emission line features (Kennicutt 1989). The traditional value $Q = 0.002 \text{ Gyr}^{-1}$ requires an unusually strong suppression of star formation in irregular galaxies, the surface brightness of which is not necessarily very low.

We do not consider intermittent star bursts, which are often invoked in the literature to account for faint blue galaxies. We consider that the star formation activity is steady and continuous at least for the majority of galaxies. The galaxies are highly gaseous shortly after their birth, and the star formation rate per galaxy can be 4 times than it is today. Those galaxies are seen as if they are undergoing star burst activity.

We conclude that irregular galaxies observed today formed at around $z \sim 1$, although some irregulars are formed as low as $z \sim 0.5$ or less, and some others as high as $z \sim 2$. We do not mean, however, that the irregular galaxies do not form at high $z$. Most of the galaxies formed at higher $z$, might already have been faded or accreted onto giant galaxies and they do not show up in our local sample of irregulars.

### 2.2. Disks of spiral galaxies

A similar analysis can be applied to disk components of spiral galaxies. Figure 2 shows $B - V$ versus $M_{\text{gas}}/L_B$ plot for spiral disks, where both $B - V$ and $L_B$ are corrected for the light from bulge component by assuming average disk/bulge ratios that depend on morphology (see section 3.1 below). The data are taken from RC3. A plot is also made for Irr and Sd for comparison. The tracks are calculated with a closed model.

This figure shows that the disks of late-type spiral galaxies are also young with ages around $\approx 5$-12 Gyr allowing for a large scatter, if a slight upward shift of the data due to the neglect of $\text{H}_2$ gas is taken into account. The plot for Sa indicates that some of these might be as old as the spheroids.

![Fig. 2. — Same as Fig. 1, but for the disk components of Sa, Sb, Sc galaxies. The data for Sd and Im galaxies are also added. Data are taken from RC3.](image)

The age of the disk of Sb - Sc galaxies inferred this way is consistent with the age of the oldest disk stars (7.5–11 Gyr) estimated from nearby white dwarfs (Winget et al. 1987; Wood 1992).

For bulges of spiral galaxies it is reasonable to suppose that they formed very early, $z \gtrsim 3$, from family resemblance with elliptical galaxies, if they indeed formed so. The resulting picture is that spiral disks formed as intergalactic gas accreted onto preexisting bulges and star formation began in the disk at $z \sim 1 - 3$.

### 3. The model

#### 3.1. Galaxy formation epoch and the evolution model

We assume that spheroids (ellipticals and bulges of spiral galaxies) formed at high $z$ ($z > 5$) by a single short burst event. The stars have to be formed from the initially collapsing gas faster than the collapse time to avoid disk formation (Eggen et al. 1962). The duration of the burst is taken to be 0.125 Gyr, i.e., the star formation rate $Q_*$ (hereinafter the star formation rate is denoted as $Q_*$) being effectively 40 times the solar neighbourhood value (e.g., Sandage 1986). These galaxies evolve passively after the burst.
The problem inherent in the presently available stellar population synthesis models is that they do not reproduce the UV spectrum of average elliptical galaxies today. It shows a significant UV component and frequently an upturn shortward of 2000 Å (Bertola, Capaccioli & Oke 1982; Burstein et al. 1988). In the models of passive evolution the UV component rapidly dies off a few Gyr after the burst. The UV component of elliptical galaxies, however, plays very little role in the quantities that we discuss in the present paper. No effect is expected in the $K$ band until one samples galaxies above $z \simeq 6$. In this pass band the effect is visible only in the high redshift tail of the redshift distribution at $K > 23$ mag. For the $I$ band the effect appears only above $z > 2$, and a minor change is expected only for $I \gtrsim 25$. For the $B$ band we expect some effect for redshifts as low as 0.5, but the spheroids play only a minor role in this pass band, and the presence or absence of the UV component does not change any predictions, unless elliptical galaxies are specifically selected from the sample. For this reason we can ignore the problem of the disagreement of the passive evolution model with the UV observations.

We represent spiral galaxies with two morphological types, Sab and Sc. We assume that they consist of old spheroids and disks which formed typically at $z \sim 1-2$. We adopt for the disk components a model where gas continuously accretes onto spheroids, making spiral disks with $\epsilon$-folding time $Q_{in}^{-1} = 5$ Gyr ($Q_{in}^{-1}$ is the inverse of the infall rate), which corresponds to $z \sim 1-2$. The star formation rate $Q_*$ is set equal to the value in the solar neighbourhood, $Q_* = 0.2$ Gyr$^{-1}$, irrespective of galaxy types. We use the stellar population synthesis model of Arimoto, Yoshii & Takahara (1992) to accommodate gas infall. This infall model gives evolutionary tracks significantly different from the ones based on a closed model shown in Fig. 2 for a high $Q_*$ case, but the self-consistency between the input and output is maintained for (age, star formation rate) versus (colour, age). The bulge fraction in the blue light is taken to be 0.3 for Sab and 0.1 for Sc in agreement with the analysis of Kent (1985) after the colour transformation. We remark that we adopt here a model of disk formation exponential in time with $\epsilon$-folding time $Q_{in}$ for simplicity. The formation epoch of irregular galaxies is taken to be 8 Gyr back from the present for simplicity of the model, although the actual formation epoch spreads over a wide range of age. We assume a universal star formation rate, the same value as that for disks.

We take the age of the universe to be 15 Gyr, but only minor modifications are caused if we take it to be 13.5 Gyr (e.g., E galaxies are slightly bluer, and evolution is a little stronger etc.). The Hubble constant enters into our scenario only through the evolution time-scale of stars. We assume the Hubble constant to have the value specified by the assumed age of the universe and the specific cosmology we consider.

The parameters of our model are summarized in Table 1. Some basic predictions for galaxy properties, bulge fraction (input), $M_{baryon}/L_B$, gas fraction, $B - V$, $V - R$, $V - I$ and $V - K$ colours at $z = 0$, are presented in Table 2 (discussion is deferred to later sections). We use the standard Johnson-Morgan-Cousins colour band system, unless otherwise explicitly denoted. The evolution of the light emitted by E, Sc and Irr galaxies is shown in Fig. 3 for the rest frame $B$ and $K$ bands. Spheroids follow the standard passive evolution for both pass bands. The brightening of 0.3 mag in $B$ between $z = 0.3$ and 0.6 is consistent with the observation for red galaxies in the Lilly et al. (1995) sample, in particular for $q_0 = 0$ cosmology. Sc galaxies hardly evolve in the $K$ band. In the $B$ band, weak evolution is visible only between $z = 0$ and 0.5, only in the epoch after gas infall has ceased. The evolution between $z = 0$ and 0.5 is about a half mag. (This is compared to Lilly et al. 1995, who reported 1 mag evolution of $L_B^*$ from $z = 0$ to $z = 0.6$; they have not seen a change of $L^*$ above $z > 0.75$, which is consistent with our model).

Below $z \leq 1$, the galaxies that have undergone the fastest evolution are Irr, but the total increment in the $B$ band luminosity is only 0.8 mag between $z = 0$ and

### Table 1: Assumed history of star formation in galaxy.

<table>
<thead>
<tr>
<th></th>
<th>$t_G$ (Gyr)</th>
<th>$Q_*^{-1}$ (Gyr)</th>
<th>$Q_{in}^{-1}$ (Gyr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>spheroids</td>
<td>15</td>
<td>0.125 (burst)</td>
<td>instantaneous</td>
</tr>
<tr>
<td>disks</td>
<td>15</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>irregulars</td>
<td>8</td>
<td>5</td>
<td>instantaneous</td>
</tr>
</tbody>
</table>
Table 2: Properties of galaxies at the present epoch.

<table>
<thead>
<tr>
<th></th>
<th>E/S0</th>
<th>Sab</th>
<th>Sc</th>
<th>Im</th>
<th>disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>bulge fraction ($L_B$)</td>
<td>1</td>
<td>0.3</td>
<td>0.1</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>bulge fraction ($L_K$)</td>
<td>1</td>
<td>0.5</td>
<td>0.15</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>$M_{\text{baryon}}/L_B$</td>
<td>8.4</td>
<td>4.7</td>
<td>3.6</td>
<td>1.8</td>
<td>3.1</td>
</tr>
<tr>
<td>gas fraction</td>
<td>0</td>
<td>0.10</td>
<td>0.18</td>
<td>0.32</td>
<td>0.22</td>
</tr>
<tr>
<td>$B - V$</td>
<td>0.98</td>
<td>0.68</td>
<td>0.57</td>
<td>0.46</td>
<td>0.51</td>
</tr>
<tr>
<td>$V - R$</td>
<td>0.90</td>
<td>0.73</td>
<td>0.68</td>
<td>0.61</td>
<td>0.65</td>
</tr>
<tr>
<td>$V - I$</td>
<td>1.69</td>
<td>1.42</td>
<td>1.32</td>
<td>1.18</td>
<td>1.27</td>
</tr>
<tr>
<td>$V - K$</td>
<td>3.11</td>
<td>2.87</td>
<td>2.66</td>
<td>2.42</td>
<td>2.56</td>
</tr>
</tbody>
</table>

0.8. Of course, the evolution is much faster in the UV light, and the $E$ correction for the $B$ count amounts to $\approx 2$ mag in the same redshift range. This is almost the maximum evolution that can be attained with a conventional stellar population synthesis model. Lilly (1993) and Phillips & Driver (1995) assumed significantly faster evolution ($\Delta m = 4$ mag between $z = 0$ and 0.4, and 2.5 mag between $z = 0$ and 0.5, respectively).

3.2. Local luminosity function

Another input to the model that deserves discussion is the local luminosity function (LF). We need the morphology-type dependent luminosity function. The only case where we know such LF reasonably well is that for the Virgo cluster (Bingelli, Sandage & Tammann 1988). The LFs, when galaxies are classified into morphological types, show cutoffs in both bright and faint ends. On the other hand, we know reasonably well that the LF summed over all morphological types behaves like the Schechter function (Loveday et al. 1992, Lin et al. 1996, Ellis et al. 1996), although its faint end is uncertain. We adopt as a fiducial LF the one reconstructed by Lilly (1993), which takes account of all these features (reproduced in Fig. 4). In this figure Sdm and dIrr are plotted separately, but our results do not depend on whether we keep the dIrr component or drop it. Hereinafter, we simply use terminology of Irr for the sum of Sdm and dIrr.

The total LF is represented by a Schechter function with $\alpha = -1.15$, $M^*_B = -19.6 + 5 \log h$ mag, and $\phi^* = 0.018h^3$ (Mpc)$^{-3}$, where an upward shift by 0.1 dex is made for the normalization. This corresponds to local luminosity density $\mathcal{L} = 2.11 \times 10^8 h L_\odot (\text{Mpc})^{-3}$. We remark that the normalization of the LF has a substantial uncertainty. Our adopted normalization is consistent with those of Efstathiou, Ellis & Peterson (1988) and of Ellis et al. (1996) with the luminosity density $1.93$ and $2.05 \times 10^8 h L_\odot (\text{Mpc})^{-3}$, respectively, but is higher than that of Loveday et al. (1992), $1.35 \times 10^8 h L_\odot (\text{Mpc})^{-3}$. We see a 50% uncertainty in $\mathcal{L}$ among the widely accepted LFs.

We remark that the slope of the faint end is not very important to the overall shape of the number

Fig. 3.— Evolution of the rest frame $B$ and $K$ band luminosity for E/S0, Sc and Irr galaxies in our model.

2This is smaller than the uncertainty seen in $\phi^*$. The determination of $\phi^*$ is correlated with $L^*$, and the resulting uncertainty in $\mathcal{L}$ is smaller than that in $\phi^*$.
counts, unless the faint tail of the LF rises so sharply that it leads to a substantial enhancement of the integral, i.e., $\alpha \lesssim -1.6$. The contribution to the number count (see eq. [1] below) is luminosity weighted, as $\sim L^{3/2} \phi(M)$, so that the behaviour of the number count is basically determined by galaxies with the characteristic luminosity.

On the other hand, the LF of irregular galaxies may well be higher by a factor of two or more, which increases the contribution from irregular galaxies by this amount. In this paper we adopt the above LF as a fiducial choice and then discuss whether the modifications necessary to explain the observation, if any, are within the uncertainties of the current LF, rather than modifying the adopted LF.

### 3.3. Cosmology

The differential number count of galaxies is given by

$$n(m, z) = \frac{\omega}{4\pi} \frac{dV}{dz} \phi(M),$$  \hspace{1cm} (1)

where $\omega$ is solid angle, $V$ is the comoving volume, $\phi$ is the LF, and the relation between $m$ and $M$ in the $\lambda$-pass band is given by

$$m_\lambda = M_\lambda + K_\lambda + E_\lambda + 5 \log(d_L/10\text{pc}),$$  \hspace{1cm} (2)

with $d_L$ the luminosity distance. The $K$ correction for the optical band is taken from Fukugita, Shimasaku & Ichikawa (1995). We adopt the $K$ correction of Cowie et al. (1994) for the $K$ band. There is little difference among authors for $K$ corrections for any colour bands other than far UV. We also refer to Fukugita et al. (1995) for the transformation of magnitudes between the different colour band systems, which is extensively used in this paper. The $E$ correction is calculated according to the prescription given in section 3.1 above.

We consider a number of cosmological models when we discuss the $K$ band count, which shows the largest power in discriminating among cosmological models. For other colour bands we are confined mainly to two cases: (i) open universe with $\Omega = 0.1$, and (ii) $\lambda$-dominated universe with $\Omega = 0.1$ and $\lambda = 0.9$, as an extreme case, although such high $\lambda$ seems to be excluded from the statistical lensing. $\Omega = 1$ models fail to reproduce the data for the $K$ band count, and hence are omitted from most of our considerations.

### 4. Predictions of the model

#### 4.1. Galaxies in the $K$-band

**Number count**

Figure 5 shows galaxy number counts in the $K$ band. The data are taken from Djorgovski et al. (1995), Gardner et al. (1993) and Soifer et al. (1994) for faint counts, and Glazebrook et al. (1994) and Mobasher, Ellis & Sharples (1986) for brighter counts. The curves are shown for four cosmology models: $\Omega = 1$; $\Omega = 0.1$ open model; $(\Omega = 0.1, \lambda = 0.9)$; and $(\Omega = 0.3, \lambda = 0.7)$. We can see gross agreement between the models and the observation for open and $\lambda \neq 0$ models. The predicted count for the $\Omega = 1$ model falls short of the observed count beyond 20 mag, by a factor of 4 at 23 mag, showing that $\Omega = 1$ model is disfavoured. This conclusion would not be modified unless there are unexpectedly many red dwarfs in the local LF (so that $\alpha \approx -2$)
at very faint magnitudes, or the basic assumptions of the present model (conserved number of galaxies; early spheroid formation etc.) are abandoned; see the discussion section below.

Looking at details we note a few features: a good agreement at bright magnitudes indicates that the normalization of the $K$ band count is given correctly with the $B$ band LF and the colour transformation without further adjustment. The observed counts are slightly higher at $K = 17-18$; the data look as if there is a mild change in the slope at this magnitude, while such change is not accounted for by the usual $K$ or $E$ correction. Another feature is that the prediction of the ($\Omega = 0.1, \lambda = 0.9$) model overshoots the data of Djorgovski et al. for the range 20-23 mag by a factor of $\sim 2$. On the other hand, this $\lambda$-dominated model just fits the data of Soifer et al. The survey areas for these deep counts are only 1-2 square arcminutes for the above two surveys, and 16 square arcminutes in the Gardner et al. survey. It is likely that the data suffer from the effect of large-scale inhomogeneity beyond $\sqrt{N}$ error estimates. For this reason we cannot yet rule out the $\lambda$-dominated model from the analysis of these counts. A deep survey of larger area is highly awaited in this regard.

We find that some small wiggle is induced to the $N(m)$ curve if the epoch of burst-like spheroidal formation is as low as $z = 5-6$. The effect is more clearly visible in the redshift distribution. Nevertheless, the gross feature of $K$ band count is fairly insensitive to the model details; it is more sensitive to cosmology.

It is generally expected that the $K$ band light is sensitive to the old population. We show in Fig. 6 the fraction of light in the $K$ band arising from spheroidal components for an $\Omega = 0.1$ universe. (A similar plot is also shown for the blue light for comparison.) This figure shows that $\gtrsim 60\%$ of light comes from spheroidal components in the entire magnitude range that concerns us, confirming the expectation that $K$ band counts are a good probe for old population. Since we understand the evolution of spheroids reasonably well, there is no much difference among predictions of different authors. This makes $K$ counts suitable to study cosmology, especially for a test for the cosmological constant. The uncertainty present in the data, however, does not allow us to make a conclusion. For the blue light the fraction of spheroid contribution is about $10\%$ for $B_J \gtrsim 22$ mag.

**Redshift distribution**

![Fig. 5.— $K$ band galaxy number count, as compared with the model predictions for four cosmology models. Data are taken from Djorgovski et al. (1995) (solid squares), Soifer et al. (1994) (crosses), Gardner et al. (1993) (solid triangles), Glazebrook et al. (1994) (open triangles) and Mobasher et al. (1986) (open circles).](image)

![Fig. 6.— Fraction of light emitted by spheroids from galaxies which are observed at specified magnitude.](image)
Three panels in Fig. 7 show the redshift distribution for the magnitude range (a) $K = 17 - 18$, (b) $K = 19 - 20$ and (c) $K = 23 - 23.5$. The prediction is compared in (a) with the $z$ survey data of Songaila et al. (1994) after normalizing them to the count data with the sample incompleteness taken into account. The figure shows good agreement for the global shape, although the data are higher than the prediction by 20% (note that this is the magnitude where the disagreement between prediction and data becomes maximum, as we noted above) and they lack a high $z$ tail above $z \approx 1$. At this magnitude 15% of galaxies are not given redshift data, and it is conceivable that they are missed by redshifting the characteristic [O II] line out of the spectroscopy window, as it is more clearly seen in their fainter magnitude sample, where basically no galaxies above $z = 1$ are catalogued. We remark that shoulders or wiggles seen in summed redshift distribution are artefact of representing galaxies with only four distinct types. Since morphology is a continuous class, these curves must be sufficiently smeared when we compare them with the observation.

The calculation indicates that spiral galaxies dominate at lower redshift, whereas galaxies at higher redshift are predominantly of early-type. For $K = 17 - 18$ mag, the distribution consists of spiral galaxies with $z_{\text{med}} \approx 0.4$ and early type galaxies with $z_{\text{med}} \approx 0.8$. Although the morphologies of the $K$ selected sample are not available, one can use emission features to show consistency with this prediction. We show in Fig. 8 equivalent widths of [OII]λ3727 emission lines for galaxies in the same magnitude range. The figure shows a trend of decreasing equivalent widths with increasing $z$. Though the evidence is not compelling, these data are consistent with increasing fraction of early type galaxies with increasing $z$, as the model calculation predicts. This may appear to be in contrast to the claim that emission lines become stronger as $z$ increases. Of course, these two statements are not contradictory: in our case we confine ourselves to a fixed magnitude range. A general trend of strengthening emission features to higher $z$ is understood as star formation being more active in spiral disks, as in our model.

The maximum redshift reaches $z = 1.5$ even at $K = 17 - 18$. This increases to $z = 3.5$ at $K = 19 - 20$ and to $z > 5$ at $K = 23 - 23.5$. These maximum redshifts are so high that they allow exploration of the formation and early evolution history of spheroids, if
these high redshift tails can be sampled. At the deepest magnitude, $K = 23 - 23.5$, $z_{med}$ of elliptical galaxies is 3.5, although 60% of galaxies are spiral galaxies at around $z \sim 2$. The high redshift tail of $z > 6$ picks up UV emission from elliptical galaxies, and is particularly sensitive to the formation history. Conversely, the UV from spheroids does not contribute until this very high $z$ is reached at the faintest magnitudes; the prediction depends solely on optical emission, the evolution of which is reasonably well understood within a passive evolution model.

Another noticeable feature is a small fraction of irregular galaxies, which increases only a little with magnitude. The dominance of giant galaxies means that the effect of evolution is very small as a whole, as often said is consistent with no evolution, at least for $K < 19$ mag (e.g., Songaila et al. 1994).

If the burst-like formation epoch of elliptical galaxies is lower than $z = 5 - 6$, we expect an appreciable fraction (15%) of galaxies having this redshift even in a $K = 17 - 18$ mag sample (see Fig. 9). This fraction increases to 30% at $K = 19 - 20$ mag. Though this looks somewhat unusual, we are not able to exclude this possibility immediately because of the sample incompleteness of the redshift survey of Songaila et al. (1994), which amounts to 15% at $K = 17 - 18$ mag.
4.2. Galaxies in the $B$ band

Number counts

The astrophysics of the $B$ band count is very different from that in the $K$ band, as expected from Figure 6 shown above. The light, especially that from faint objects, is dominated by young components, disks and irregular galaxies.

We present in Fig. 10 the prediction of the $B_J$ band count for the two cosmological models: (a) $\Omega = 0.1$, and (b) ($\Omega = 0.1$, $\lambda = 0.9$). The data are taken from Metcalfe et al. (1995), Tyson (1988), Maddox et al. (1990), Jones et al. (1991) and Lilly et al. (1991). We do not calculate the counts beyond $B = 26$ mag (predicted median redshift is 0.8) because of the lack of reliable $K$ and $E$ corrections for redshift above $z = 2$. The thick line represents the total count, and the thin solid line and the dotted lines are E/S0 and spiral galaxies, respectively. The agreement between the calculation and the data is reasonable, although the former is short of the latter by 0.3 dex at the faintest magnitude in (a). The contribution from spiral galaxies remains significant even at faint magnitude, but the significance of E/S0 galaxies diminishes for fainter magnitudes, due to a large $K$ correction. The most conspicuous in the figure is a rapid increase of Irr (dashed line) as we go to fainter magnitudes: the contribution to the counts relative to spiral is 10% at 17 mag, but they contribute equally at 24 mag. This is explained by a combination of three effects: (i) Irr’s are located at relatively near distances, and so the reduction of spatial volume in a relativistic cosmology is only modest; (ii) the blue-weighted nature of spectrum gives only small $K$-corrections; and most importantly, (iii) these galaxies formed at low redshift and a large evolutionary effect is present. These effects together make the slope of Irr counts quite steep. We can conclude that these irregular galaxies are the agent that yields a steep slope of the $B$ count. We note that the component that gives an important contribution at 22-25 mag is not “dwarf” galaxies, but is those which are on the immediate extension of late-type spiral galaxies to the fainter side. These galaxies have sub $L^*$ luminosity today, but were nearly as bright as giant spiral galaxies for a few Gyr after their births. This explains the “faint blue galaxy problem”.

In the above figure, we see a better fit with a high $\lambda$ model, but we do not claim that this model is favoured. The discrepancy between the prediction...
and data seen in $\Omega = 0.1$ model almost disappears, if the normalization of the LF for Irr galaxies is increased by a factor of $\approx 2-3$, which is within the observational uncertainties, but also is indicated by a few analyses of local LF including blue galaxies (Metcalfe et al. 1991; Marzke et al. 1994; Lilly et al. 1995; SubbaRao et al. 1996) 4. Alternatively, the possibility also exists that the LF of irregulars is actually lifted as $z$ increases (Ellis et al. 1996), and the normalization of the local LF for irregulars used in this paper is correct. This requires that the number of irregular galaxies decreases with decreasing redshift, for instance by these galaxies being accreted onto nearby giant galaxies. These “minor” mergers modify the property of giant galaxies very little, and this possibility seems perfectly viable, as a minimum modification of the scenario presented in this paper. On the other hand, it is unlikely that these population has simply faded away.

BES have discovered that [OII] emission increases rapidly with increasing magnitude. The fraction of galaxies that show equivalent widths larger than 20Å increases from 15% at $B_J \leq 17$ mag to as much as 55% at $B_J \sim 21$ mag. Koo & Kron (1992) ascribed this increase to the increase of the fraction of subluminous late type galaxies, which generally are strong [OII] emitters, as one goes to fainter magnitude. We agree that this is one cause, but not the major one. In our model, this increase is caused by both an increase of Irr fractions as a result of a steep slope of $N(m)$ for Irr, and an increase of gas in spiral galaxies. Straightforward reading of the [OII] equivalent width distribution of Kennicutt (1992) (see his Figure 9) gives 13% of normal galaxies having $> 20\AA$ [OII] equivalent widths, consistent with the BES $B_J < 17$ mag sample. The disks at $z \sim 0.3 - 0.4$ are two times more gaseous than at $z = 0$. A simple calculation using the [O II] distribution in the Kennicutt figure leads to the result that the fraction of galaxies having EW([OII]) $> 20\AA$ is 45% at $B_J \sim 21$. This is consistent with the result of BES.

4The rise of LF towards faint magnitude has also been noted in the Virgo LF (Binggeli, Sandage & Tammann 1988). In this case the rise is ascribed to that in dwarf spheroidals, but not irregulars. It is, however, likely that irregulars evolve to dwarf spheroids in the environment rich of galaxies, since the gas driven out by supernovae may easily be accreted onto giant galaxies rather than onto the original galaxies, and irregulars may readily evolve into dwarf spheroidals. Therefore, it is likely that dwarf spheroidals are descendants of high $z$ irregulars and these two observations are mutually consistent.

In our explanation of the $B$ band count, we do not particularly invoke incidental star burst activity. Star formation takes place steadily as it does today, but those galaxies at $z \sim 0.5 - 1$ are much more gaseous: the gas in Irr 1 Gyr after their birth is 3 times that of today, and so the global star formation rate per galaxy is 3 times higher, which might give the appearance that those galaxies are undergoing star bursting activity.

Redshift distribution

The redshift distribution of the sample selected in the $B$ band corroborates the view given above. In Fig. 11, we compare the prediction with the observations of Glazebrook et al. (1995a; solid histogram) and of Cowie et al. (1996; dotted histogram) for $B_J = 22.5 - 24$ mag. We can see a good agreement between the two for the dominant feature around the peak. The redshift data are normalized to the observed count. An interesting fact is that the observed distribution looks quite similar to that of spiral (plus E/S0) galaxies, while the normalization of the former is higher by a factor of two. This is the feature that has puzzled many cosmologists after the discovery by British groups (BES; Colless et al. 1990). In our

Fig. 11.— Redshift distribution of galaxies selected with $B_J = 22.5 - 24$ mag, as compared with the model prediction. Data are taken from Glazebrook et al. (1995a; solid histogram) and Cowie et al. (1996; dotted histogram), and normalized to the count data.
Fig. 12.— Galaxy number count of morphologically classified sample, compared with the model prediction for an open universe $\Omega = 0.1$. Data are taken from Glazebrook et al. (1995b) (solid circles), Abraham et al. (1996) (open circles) and Driver et al. (1996) (open triangles, for (b) only).

model this factor two difference is explained by irregular galaxies which were almost as luminous as giant spiral galaxies in the blue band. The survey selected in the blue light preferentially samples actively star forming components, which were newly formed in the near past. At this magnitude the contribution from E/S0 is quite small.

The presence of high $z$ tail has been a matter of debate. Earlier observations (BES; Colless et al. 1996; Lilly, Cowie & Gardner 1991; Glazebrook et al. 1995a) have claimed the absence of the high $z$ tail. On the contrary, some recent observations (Cowie et al. 1996; Koo 1996) indicate the presence of the tail. Our model predicts a small high redshift tail which arises from luminous spiral galaxies; we cannot eliminate entirely the high $z$ tail. The size of tail depends largely on the amount of evolution of spiral galaxies. A large high $z$ tail of Cowie et al., if confirmed, suggests that the evolution should be stronger than is in the present model.

4.3. Galaxies in the $I$ band

**Number count**

Fig. 13.— Same as Fig. 12, but for the $(\Omega = 0.1, \lambda = 0.9)$ model.

The novel feature for the $I$ band is that morphologically classified number counts are available (Glazebrook et al. 1995b; Driver et al. 1996; Abraham et al. 1996) to $I = 24$ mag. At this magnitude we expect the median redshift to be unity. We compare the prediction of the $\Omega = 0.1$ model with the observation in Fig. 12 for E/S0 (panel b), spiral (panel c), Irr (panel d) and the total sample (panel a). We see a good agreement for spiral galaxies to $I_{F814W} = 22$ mag. For E/S0 galaxies the predicted curve is somewhat lower by $\approx 0.1 - 0.2$ dex to the same magnitude, but the statistics are poor for this type. The disagreement is significant for Irr. The important feature here, however, is that the steep slope of the Irr counts (index=$0.64 \pm 0.05$ for $I = 19 - 22$ mag) is correctly reproduced by a sub $L^*$ population of young, quickly evolving galaxies. That the predicted counts of irregulars are lower by a factor of three is similar to the problem we encountered with the blue count, and can be accounted for if the LF of Irr is increased by a factor of 3.

Glazebrook et al. (1995b) have noted that the normalization of their $I$ count is higher than predicted from the local LF in the $B$ band. In our calculation this discrepancy is not so conspicuous: a half of the discrepancy is accounted for by our higher normalization of the local LF, which is larger than that of
Loveday et al. (1992) by 0.15 dex. We still see a discrepancy for the amount of 0.12 dex at $I_{F814W} = 22$. This is reduced to 0.05 dex if the normalization of the Irr-LF is multiplied by a factor of 3.

At fainter magnitudes the observed counts are somewhat higher than calculated. This is particularly true for E/S0 galaxies. We note that the shape of the prediction of E/S0 galaxies is rather generic and it is not easy to modify the prediction. On the other hand, somewhat higher observed counts of spiral galaxies may be explained by increasing evolution of spiral galaxies. It may also be possible that there is a misclassification between spirals and Irr galaxies, since the classification becomes increasingly ambiguous towards the faintest magnitude: the number count of Irr may not flatten but increase linearly towards the fainter magnitude, while the number of spiral galaxies may rise close to the predicted curve. It is also possible that the counts from $I > 22$ mag survey are largely affected by large-scale inhomogeneity of the galaxy distribution, since the survey fields are quite small.

Driver et al. (1996) concluded that high $\lambda$ models ($\lambda \geq 0.7$ in a flat cosmology) are excluded from a comparison of their E/S0 counts with their model prediction, as the predicted count with high $\lambda$ overshoots the observation. Our model calculation, however, does not confirm their conclusion. We present in Fig. 13 the predicted counts for ($\Omega = 0.1, \lambda = 0.9$) model, where the discrepancy between the prediction and the data almost disappears to the faintest magnitude. In particular, the prediction of E/S0 is consistent with data of Driver et al. We note that the main difference between our model and Driver et al.’s lies in the normalization of E/S0 galaxy counts, i.e., a much higher normalization adopted by the latter work.

Redshift distribution

Lilly et al. (1995) have carried out a large redshift survey to $I=22$. Their data are compared with the prediction in Fig. 14 (a). The predicted redshift distribution agrees with the data very well, with the normalization, however, smaller by 20% for the open cosmology. The case of $\lambda$ dominated universe ($\Omega = 0.1, \lambda = 0.9$) is displayed in Fig. 14 (b). Unlike the case for the $B$ band, the distribution is dominated by spiral galaxies, and the contribution from E/S0 and Irr is quite small. The small contribution from Irr is understood by the fact that the very active star formation for $0.5 < z < 1$ largely affect the $B$ band observations, whereas $I$ band observations are more sensitive to the total number of stars in the galaxy, and stars are not yet accumulated before $z = 0.5$. We note that the evolution of spiral galaxies is less than 0.5 mag to $z = 1$, and the evolutionary effect is not manifest in the $z$ distribution.

The prediction for the redshift distribution is shown in Fig. 15 for $I = 23 - 24$ mag. We note that E/S0 counts are always lower than the contribution from spiral galaxies for all $z$. This is different from what we saw for the $K$ counts, where the high redshift part was dominated by early type galaxies.

4.4. Colour distribution

The colour distribution is shown in Fig. 16. We take the $B_I - R_F$ data from a compilation of Koo & Kron (1992) for the magnitude between $B_I = 19$ and 27. The data for the brightest magnitudes ($B_I = 14 - 16$) are $B - V$ from Gronwall & Koo (1995). The prediction, denoted with dotted lines, agrees well with the data to $B = 24$ mag. We see that the data are slightly bluer for fainter magnitudes. Better agreement is achieved by increasing the irregular popu-
Fig. 15.— Prediction of the redshift distribution for the $I = 23 - 24$ mag sample for the open universe model.

ulation by a factor of 2, although the prediction for $B_J = 25 - 26$ mag is still somewhat (0.2 mag) redder. We do not calculate the colour distribution for $B_J > 26$ for the reason given in section 4.2 above.

4.5 The Mg II absorption-line selected sample and the constraint on the luminosity evolution

Steidel et al. (1994) have studied properties of 58 galaxies that yield Mg II absorption lines near the line of sight to quasars. Giant galaxies are always found close to the quasar sightline along which Mg II absorption lines are detected, and conversely all giant galaxies located close to the quasar sightline cause Mg II absorption in the quasar spectrum. Their conclusion is that those galaxies that cause Mg II absorption lines are giant galaxies and these galaxies hardly evolve at least between $z = 0.3$ and 1.0: the allowed amount of evolution is $0.1 \pm 0.2$ mag in the rest frame $B$ band for this redshift interval. This puts a very strong constraint on the model. In our model, E/S0 undergo evolution by a half magnitude and Sc galaxies by 0.2 mag (see Fig. 17). While our evolution of E/S0 galaxies looks faster, the fraction of galaxies that show E/S0 colours is small in the Steidel et al. sample, and their data do not give a strong constraint on the evolution of E/S0 galaxies. Irregular galaxies also evolve faster, but such galaxies do not yield Mg II absorption lines and are excluded from the sample; hence no constraint is obtained on the evolution of irregulars. Therefore, the prediction of our model is consistent with the result from the Mg II sample.

We note that Sc galaxies undergo evolution, after gas infall has ceased, by 0.4 mag between $z = 0$ and $z = 0.3$, which is out of the range surveyed by Mg II absorption lines. It is interesting to note that this causes brightening of $L^*$ below $z = 0.3$, and hence increases the number of super $L^*$ galaxies observed at higher redshift by a factor of 1.7 times. Sc is the median colour of Mg II absorbers, and this brightening may account for the offset in the normalization (by a factor of 1.5, if the normalization of the local LF used in the present paper is adopted) between the Mg II sample and the local LF as found by Steidel et al.

4.5. Magnitude-redshift relation

In order to summarize the basic prediction of our model, we present in Fig. 18 the redshift as a func-

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5See Schade et al. (1996), however.
Fig. 17.— $B$ band luminosity of giant galaxies in the Mg II quasar absorption line sample of Steidel et al. (1995). Data points denoted by thick lines represent the total sample, and those by thin lines show the sample of red galaxies with $B - K > 3.7$, nominally corresponding to elliptical galaxies. Two curves show the prediction for E/S0 and Sc galaxies with their luminosity normalized at $z = 0.4$.

Fig. 18.— (a) Median (solid curves), quartile (dashed curves) and 90 percentile (dotted curves) redshifts predicted in the model as a function of magnitude for $B$ selected samples.

4.6. Baryons in stars and the gas

We calculate the amount of baryons frozen into stars as a function of look-back time in Fig. 19. The solid, dotted and dashed curves indicate spheroids, spheroids + disks, and total = spheroids + disks + irregulars, respectively. The mass of spheroids is constant in this redshift range as assumed. The mass in disks increases to lower redshift. The apparent rapid increase towards $z = 0$ in this figure, however, is an artefact of the compression of the time scale of the abscissa towards $z = 0$; the increase close to $z = 0$ is actually quite slow if the diagram is represented as a function of time rather than redshift.

The prediction of $M_{\text{star}}/L_B$ for the spheroids with the population synthesis model is far from robust, since it depends significantly on the lower mass cut-off, even if the initial mass function is fixed. Charlot, Worthey & Bressan (1996) have given a compilation of $M_{\text{star}}/L_V$ for widely accepted models, which give $M_{\text{star}}/L_V = 6 - 8$ for the age 13-15 Gyr. We adopt $M_{\text{star}}/L_B = 8.4$, which agrees with the value obtained from kinematics of elliptical galaxies by van der Marel (1991), if $h = 0.7$.

We note that about 2/3 of baryons in stars today are in spheroids, and only 1/3 in disks. This agrees with the estimates obtained with different assumptions (Fukugita et al. 1996; see also Persic & Salucci 1992). It is interesting to note that the contribution from irregulars to the stellar mass density is very small in spite of their drastic contribution to the $B_J$ counts. We note that $M(M_{\text{star}}/L_B) = 3.1$ and 1.8 for disks and irregular galaxies in our model. $M_{\text{star}}/L_B$ for galaxies of various morphology types are given in Table 2 above.

We also plot in Fig. 19 the evolution of the neutral atomic gas density in units of the critical mass density obtained from surveys of damped Lyman $\alpha$ systems (Wolfe et al. 1986; Lanzetta et al. 1995). We adopt for $z \geq 3$ the data of Storrie-Lombardi et al. (1996), which update those of Lanzetta et al. (1995): the data at high $z$ have gone down by a factor of two, and this
is ascribed to small statistics and an underestimate of statistical errors of the Lanzetta et al. sample. The point at $z = 0$ is taken from an HI survey of Rao & Briggs (1993) (see also Fall & Pei 1993). It is interesting to observe that the amount of decrement in gas from $z = 3$ to $z = 0$ is just consistent with the increment of baryons in disk stars in the same redshift range. This is somewhat different from the claim by Lanzetta et al. (1995) who regarded the consumption of neutral gas as being used to form all stars in the universe. Accepting the new result of Storrie-Lombardi et al., the baryon budget calculated here indicates that the decrement of the neutral gas is significantly smaller (by a factor of 3) than the total amount of baryons frozen in stars. This favours the picture that most spheroids existed prior to $z = 3$, and the neutral gas observed at this epoch basically went into stars in disks and irregulars.

In our model the residual gas left in galaxies is $\Omega_{\text{gas}} = 0.0002$. This is compared with $\Omega_{\text{HI+HeI}} = 0.0003$ from an HI survey of Rao & Briggs (1993). This residual gas still causes star formation with a rate of $0.016 M_\odot h^3 \text{ Mpc}^{-3} \text{ yr}^{-1}$ which is compared to $0.026^{+0.014}_{-0.010} M_\odot h \text{ Mpc}^{-3} \text{ yr}^{-1}$ obtained for the local sample by Gallego et al. (1995) from an Hα survey. The star formation rate in our model increases rapidly to $z \sim 1$ (by a factor of 2-3). Such an increase is observed by Cowie, Hu & Songaila (1995) and by Lilly et al. (1996), but quantitatively, our increase between $z = 0$ and 1 is about 1/2–1/3 that reported by Lilly et al. (1996).

5. Discussion

We have presented a simple, but quantitative model for the history of galaxies. Most of the ingredients are not particularly new, known for a while from studies of many authors, although the interpretations may differ from author to author. Here, we have assembled them into a single model in a consistent way. The model is reasonably successful to reproduce many different features observationally found. Many aspects are checked with observations for $z \lesssim 1$, and hence the model is well constrained. On the other hand, the model is not well constrained for higher $z$, due to the lack of observations other than the number count data.

An almost inevitable consequence of the present scenario is that morphology of galaxies becomes manifest only in a later epoch. A likely control parameter is spheroid mass (Meiels & Ostriker 1984), or the virial temperature of spheroids, besides environment. We might speculate that cooling is not sufficient to
make disks when the virial temperature is high, leading to elliptical galaxies, and disks only form when associated with lower mass spheroids. It is likely that disk formation is hindered in cluster environments, since the virial temperature is quite high in clusters. Elliptical galaxies generally form from high $\sigma$ peaks of the density fluctuations, which makes the two point correlation of elliptical galaxies automatically high. In this scenario the cutoff of the elliptical LF in its faint end is obvious. Above $z \gtrsim 2$ disk galaxies would be observed as “naked bulges”; fuzzy cool cloud may eventually be assembled around the bulges as time goes on, and finally show up the full disk structure by $z \sim 1$. This implies that the size of disk galaxies was substantially smaller at $z \geq 1$.

In our model mergers do not play a major role, although the presence of the modest amount of mergers is not precluded. There is much evidence that the merger rate cannot be as high as needed to explain the sharp increase of the $B$ count data. The disk of our galaxies cannot acquire more than 4% of its mass in the past 5 Gyr, otherwise the disk scale height and Toomre $Q$ parameter would exceed the observed values (Tóth & Ostriker 1992). Much evidence from colour and emission properties of normal galaxies suggests that the star formation has persisted over the Hubble time without much change (Kennicutt 1983; Gallagher, Hunter & Tutukov 1984). This supports the view that galaxy properties have not undergone much change, as expected in the “major mergers”, at least after $z \sim 1$. (“Minor mergers”, e.g., accretion of small galaxies onto the disks might have taken place though; see below.) A high merger rate (Guiderdoni & Rocca-Volmerange 1991; Broadhurst et al. 1992) leads to a trend of decreasing redshift for fainter magnitude for redder colour bands, which however is not supported by the recent deep redshift survey ($I < 24$) from the Keck telescope (Koo 1996). More directly, the Mg II absorption-line selected sample indicates that properties of giant galaxies change very little after $z \sim 1$, indicating no evidence for bulk merging after this redshift. No data, however, can constrain the importance of mergers for $z \gtrsim 1$. Where only the count data are available, an increase in numbers and a decrease in luminosity compensate each other and modest merging does not modify the predictions. Therefore, the success of the present model does not necessarily mean the absence of merging for $z > 1$. This question is still not settled.

The epoch of the spheroidal formation is also a long standing problem. In our model, we simply assumed that the spheroid formation took place at a high redshift. An underlying idea for the early formation of spheroids is that stars must have formed within the collapse time and hence the first collapse of massive objects may be a suitable place for spheroid formation. The rise of the quasar population at $z = 4$ to 3 may also imply that spheroids formed at least earlier than quasars get active (Rees 1995). If, indeed, most of spheroids formed below $z < 5$, the light from the star formation epoch should be visible even in a $K = 18$ sample. Therefore, it will be particularly interesting to find spectroscopic features of those galaxies in the $K$ selected sample (Songaila et al. 1994) which have been missed in their spectroscopic follow-up. Perhaps, the technique similar to that developed by Steidel et al. (1996) can most efficiently be applied to such a sample. If the result excludes the possibility of these galaxies having $z = 3 - 5$, the remaining possibilities are either (i) they formed at very high
(ii) the formation redshift of spheroids is not so high, and they formed at around the same time as galactic disks, i.e., \( z \lesssim 3 \). We note that the baryons in spheroids amount to 2/3 (somewhat less in case of late spheroid formation) of total baryons frozen into stars. Then, if (ii) is true, the integrated light from high, and they formed at around the same time as galactic disks, i.e., \( z < 3 \) must be more than \( \approx 5 \) times higher than is predicted here, since star formation must have been stopped at some redshift above \( z = 1 \). Such activity can easily be detected, e.g., especially with use of narrow band filters selecting for H\( \alpha \) emission. Of course, this modifies the basic assumptions taken here and hence most of the predictions.

The evolution of spheroids is reasonably well understood, although quantitative details depend on models. The poorly-understood part is the UV spectrum. There are a number of speculations about the origin of the UV component observed in elliptical galaxies today, but there seems to be no consensus. In this paper we have passed over this problem. What we have discussed in this paper is the prediction that is not sensitive to the presence or absence of the UV component of spheroids. One specific case where such UV is important is seen in the high \( z \) tails of the redshift distributions of optically selected samples, the most notable example being “Lyman continuum break galaxies” having \( z = 3 - 3.5 \) in the \( R = 22 - 23.5 \) mag sample, as discovered by Steidel et al. (1996). In this case the observability of these galaxies is completely controlled by the UV light emitted from spheroids. In the present model, we predict that the tail of the redshift distribution of \( R = 22 - 23.5 \) sample does not extend beyond \( z \approx 2.5 \). The initial burst of spheroids does not give enough a number of Lyman break galaxies, unless the formation epoch is lower than \( z = 4 \). If, however, some star formation activities persist, e.g., those with recycled gas, it is easy to give a sufficient number of such galaxies, without modifying any other predictions discussed in this paper.

The evolution of spiral galaxies is less well understood. There are, however, a number of constraints from observations. Among them, the presence and strength of high redshift tail in the redshift distribution of a \( B \) selected sample serve as an interesting indicator for the amount of evolution of giant spiral galaxies. While it is generally agreed that the tail is not very large, it is still not settled observationally to what degree such a tail is present (see Cowie et al. 1996; Koo 1996). A very strong constraint comes from the Mg II sample, which precludes any appreciable luminosity evolution of spiral galaxies in the relevant redshift interval. On the other hand, the CFRS survey (Lilly et al. 1995) does see evolution of the characteristic luminosity \( L^* \) for blue, presumably spiral, galaxies by one magnitude (such evolution is not claimed in Ellis’ et al. 1996 work, though). In our model these two constraints are somehow reconciled in the way that evolution is faster between \( z = 0 \) to \( z = 0.3 - 0.5 \), but very slow above this redshift. This is because gas infall has almost ceased by \( z = 0.5 \), and the galaxies started to show more evolution after this redshift. Such evolution constraints, if taken literally, indicate that a spiral galaxy is not a closed system, but supplied with fresh gas down to \( z = 1 \) or less.

One of the main points of the present paper is to estimate the age of irregular galaxies and introduce them as being newly formed at low redshift. They are the agent that is responsible for the steep slope of the number count in the blue bands. These galaxies are quite gaseous, and undergo very active star formation, which may be observed as star bursts. A similar idea has already been advocated by a number of authors, in particular by Cowie et al. (1991) and Babul & Rees (1992). The difference is in the point that we have not introduced any population unobservable today and that we assume continuous star formation that is proportional to the gas abundance rather than the “burst”. The dwarf population, which is less luminous than ordinary irregular galaxies, plays no role in the results presented in this paper. There may be more irregular galaxies formed at higher \( z \), than are considered in this paper, but they should follow the same track as the disk component of spiral galaxies, and may constitute a low-luminosity tail of the LF of spiral galaxies, which is not important in galaxy number counts. The detailed shape of the subluminous part of the luminosity function is not important, unless the LF is very steep.

There is much indication that correlation of galaxies seen in blue bands is weak (Efstathiou et al. 1991; Couch, Jurcevic & Boyle 1993; Infante & Pritchet 1995), the clustering being at most comparable to that of late type galaxies. This is easy to understand: the \( B \) sample at faint magnitudes is dominated by spiral galaxies and irregular galaxies which form from the peaks of low-\( \sigma \) fluctuations and are thus least biased.

The local LF is clearly one of the most important sources of uncertainties, and it often hinders
us from making unambiguous predictions from our model. The uncertainty in the local LF is not only in the faint end behaviour, but also in its normalization. An upward shift of the normalization by 0.15 dex would bring a number of predictions of the galaxy counts in much better agreement with observations, and also it would decrease substantially the amount of evolution required by the high redshift data. Our normalization of the local LF, however, is on the high side of what is allowed by current surveys, so we cannot justify a further increase by 0.15 dex. More important is the problem of the faint end ($M_B \sim -16$ mag) of the LF. If the total LF has a flat slope ($\alpha \sim -1$) as in, e.g., Loveday et al. (1992) and Lin et al. (1996), that is compelling evidence for galaxy number evolution. Luminosity evolution does not have enough power to explain the abundance of irregular galaxies required in our analysis. This view is consistent with the LF at various redshifts derived by Ellis et al. (1996): the luminosity evolution does not have power to lift the faint end of the LF. On the other hand, if the local luminosity function shows an increase towards the faint end (Metcalfe et al. 1991; Marzke et al. 1994; SubbaRao et al. 1996), we do not particularly need number evolution of galaxies, but luminosity evolution is sufficient to explain the observations. It is also possible that irregular galaxies have evolved into dwarf spheroidals near giant galaxies or in a galaxy rich environment. In this case the rise of the LF may take place $\sim 1$ mag fainter than the typical luminosity of irregular galaxies.

We have argued that $K$ band observations provide a good tool to study cosmology. This is because spheroids always contribute significantly to the $K$ band counts and the evolution of spheroids is reasonably well known. We have concluded that $\Omega = 1$ is disfavoured by the count data. This conclusion remains true, as long as we keep our basic assumptions. If, however, mergers play an important role at high $z$, say $z \approx 2$, the $\Omega = 1$ model could be allowed. The $z$ distribution for $\Omega = 1$ cosmology has a component substantially extended to higher $z$ than in $\Omega = 0.1$ model. The median redshift of the spheroids in a $K \approx 22$ sample is about 3 (for an $\Omega = 0.1$ model), and an observation with $U$ and $G$ bands (as in Steidel et al. 1996) searching for Lyman break galaxies just hits the middle of the $z$-distribution at this magnitude. The possibility that not all spheroids are in place by $z \sim 3$ may also modify the conclusion about cosmology, and it may bring a confusion as to the interpretation of the cosmological models.

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