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TEST FOR THE COSMOLOGICAL CONSTANT WITH THE NUMBER COUNT OF FAINT GALAXIES

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ABSTRACT

Cosmological models are tested against the recent observations of the number count of faint galaxies by Tyson and of the redshift distribution of moderately faint galaxies by Broadhurst, Ellis, and Shanks, particularly with the purpose of examining whether a finite cosmological constant is allowed. Using the canonical galaxy evolution model with the assumption that the comoving number of galaxies is conserved, we have found that these data favor the low-density universe ($\Omega_0 \lesssim 0.1$) and that the high-density universe ($\Omega_0 \gtrsim 0.5$) is strongly disfavored. Furthermore, it is shown that the best agreement with the data is obtained with a sizable cosmological constant, including the case of zero curvature model ($\Omega_0 + \lambda_0 = 1$) as predicted by inflation.

Subject headings: cosmology — galaxies: photometry

I. INTRODUCTION

Whether the cosmological constant vanishes or not is among the best known classical problems in cosmology. While it is not very attractive from a purely theoretical point of view to introduce a nonvanishing cosmological constant (Λ), no observations so far seem to exclude this possibility. In fact, a nonvanishing Λ is even favored by some of the observational aspects in cosmology; if the Hubble constant H_0 is close to 100 km s^{-1} Mpc^{-1} as the Tully-Fisher method indicates (e.g. Aaronson *et al.* 1986; Tully 1988), the age of the universe is too short, if $\Lambda = 0$, to reconcile with constraints from the globular cluster age or nucleochronology.

In this *Letter* we examine cosmological models for the Friedmann universe, and in particular the existence of nonvanishing cosmological constant, against observations of galaxy number counts. There are a number of deep surveys (Peterson *et al.* 1979; Kron 1980; Jarvis and Tyson 1981; Shanks *et al.* 1984; Hall and Mackay 1984; Koo 1986; Infante, Pritchet, and Quintana 1986). We use here particularly the recently reported CCD number count of faint galaxies by Tyson (1988) in the B_J, R, and I bands, which reaches as deep as $28 B_J$ mag, and the redshift distribution by Broadhurst, Ellis, and Shanks (1988) for $B_J = 20$–21.5 mag. Although this latter survey reaches only $z \simeq 0.47$, we see that a significant constraint is derived from these data when combined with the former number count. We quote Sandage (1988) for a general review of this subject and Yoshii and Peterson (1989) and Guiderdoni and Rocca-Volmerange (1989) for the more recent work.

To carry out our analysis it is crucial to take the evolution effect of galaxies into account. We adopt the evolution model of Arimoto and Yoshii (1986, 1987) for luminosity evolution, which was also used in the recent analyses of Yoshii and Takahara (1988, hereafter YT) and of Yoshii and Peterson (1989), with some updates of parameters. We assume that the number of galaxies is conserved; i.e., that the merging effect is negligible for the majority of normal galaxies. We also assume that relative numbers of different morphological types do not change with the redshift. In our analysis the formulation given in YT is basically followed with slight changes of parameters. In particular, the K-correction is updated for early-type galaxies using the recent measurement of the spectral energy distribution (SED) for their UV part (Burstein *et al.* 1988).

II. FORMULATION

In the presence of cosmological constant, the luminosity distance is given by

$$d_L = (1+z)a_0 \sinh \times \left[\frac{c}{H_0 a_0}\int_{(1+z)^{-1}}^{1} \frac{dy}{y(\Omega_0/y - K + \lambda_0 y^2)^{1/2}}\right] \quad (1)$$

for the open ($k = -1$) universe (similar expressions for $k = 0$ and $+1$), where $\Omega_0 = \rho/\rho_{\rm crit}$ is the density parameter ($\rho_{\rm crit} = 3H_0^2/8\pi G$), $\lambda_0 = \Lambda c^2/3H_0^2$ is the normalized cosmological constant, and K is the normalized curvature ($K = kc^2/H_0^2 a_0^2$). These parameters are subject to the condition

$$\Omega_0 = 2q_0 + 2\lambda_0 \quad (2)$$

and

$$K = \Omega_0 + \lambda_0 - 1 . \quad (3)$$

The age of the universe is given by

$$t_0 = \frac{1}{H_0}\int_0^1 \frac{dy}{(\Omega_0/y - K + \lambda_0 y^2)^{1/2}} , \quad (4)$$

and the comoving volume $V(z)$ reads

$$\frac{dV}{dz} = \frac{4\pi d_L^2 c}{H_0(1+z)^2\sqrt{\Omega_0(1+z)^3 + \lambda_0 - K(1+z)^2}} . \quad (5)$$

We also define the age $t_G(z)$ of a galaxy formed at a redshift z_F by $t_G(z) = t(z) - t(z_F)$. The apparent magnitude at band λ is given by

$$m_\lambda = M_\lambda + 5 \log (d_L/10 \text{ pc}) + K_\lambda(z) + E_\lambda(z) , \quad (6)$$

where K_λ and E_λ are the K-correction and the evolution correction, respectively. The prescriptions for calculating these corrections are described in YT. We take their K-correction estimated using the SED by Pence (1976) and Coleman, Wu, and Weedman (1980), except for the UV-SED for early-type galaxies, for which we use Burstein *et al.* (1988). The evolution model of Arimoto and Yoshii (1986, 1987) that we adopted in our analysis is a Bruzual-type population synthesis model (Bruzual 1983) but is improved to account for chemical evolution.

We classify galaxies into five morphological types of E-S0, S_{ab}, S_{bc}, S_{cd}, and S_{dm} and assume the local galaxy mix taken by Yoshii and Peterson for all z. The local luminosity function of galaxies is assumed to have the Schechter form

$$\phi(L)dL = \phi^*(L/L^*)^\alpha \exp(-L/L^*)d(L/L^*) . \quad (7)$$

We adopt $\alpha = -1.11$ and $M^*_{B_J} = -19.6 + 5 \log h$ common to all morphological types as our standard choice. The coefficient ϕ^* is fixed to reproduce the observed count of galaxies at brighter magnitudes in the B_J band ($B_J \lesssim 17$ mag) (Kirshner, Oemler, and Schechter 1979; Peterson *et al.* 1986); $\phi^* = 1.56 \times 10^{-2} h^3 \text{ Mpc}^{-3}$ ($H_0 = 100h$ km s^{-1} Mpc^{-1}).

The most uncertain in the evolution model is evolution of the ultraviolet light in early-type galaxies. In particular, the origin of the observed upturn shortward of 2000 Å is still a matter of debate, which makes a construction of a reliable model quite difficult. YT simply assumed that the SED at shorter wavelengths $\lambda < \lambda_U = 3600$ Å did not change in shape but scaled only in intensity with the point at λ_U. On the other hand, Bruzual has argued that the upturn of UV is reproduced in his model with a choice of the mass fraction of stars formed in the first gigayear $\mu = 0.7$. In his model the UV flux evolves substantially stronger than that given by the prescription of YT. We take this uncertainty into account for wavelength shorter than λ_U by interpolating at each epoch between Bruzual's $\mu = 0.7$ model and the observed SED at the present epoch that is scaled in intensity to match the point at λ_U in the model of Arimoto and Yoshii. Namely, with a parameter x we write the E correction to be

$$\log\left[\frac{f_\lambda(z)}{f_\lambda(0)}\right] = x\left\{\log\left[\frac{f_\lambda(z)}{f_\lambda(0)}\right] - \log\left[\frac{f_{\lambda_U}(z)}{f_{\lambda_U}(0)}\right]\right\}_{\mu=0.7} + \log\left[\frac{f_{\lambda_U}(z)}{f_{\lambda_U}(0)}\right] \quad (8)$$

with $f_\lambda(z)$ the monochromatic emissivity at the epoch of a redshift z. The expression in braces on the right-hand side is the Bruzual model with $\mu = 0.7$. The case of YT corresponds to $x = 0$. We take $x = 0.2$ as our standard choice. It was argued by Yoshii and Peterson that a large x ($x \geq 0.5$) does not agree with the $J-F$ color distribution of galaxies.

The model of evolution longward of $\lambda_U = 3600$ Å is constrained better by the observation, and the model parameters are the same as given in YT.

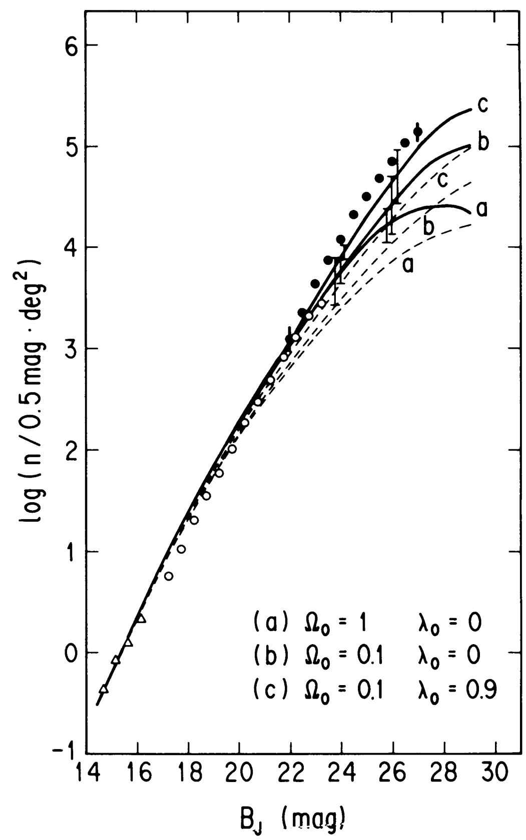

FIG. 1.—Number count of galaxies as a function of the magnitude in the B_J band. Model predictions are shown for three choices of parameters (*a*) $\Omega_0 = 1$, $\lambda_0 = 0$, $h = 0.5$; (*b*) $\Omega_0 = 0.1$, $\lambda_0 = 0$, $h = 0.7$; and (*c*) $\Omega_0 = 0.1$, $\lambda_0 = 0.9$, $h = 1.0$. Dashed curves represent the corresponding no-evolution model predictions. For error bars on the curve, see Table 1. Data points are taken from Tyson (1988) for $22 \leq B_J \leq 27$ mag (CCD) and $17 \leq B_J \leq 23$ mag (photographic), and from Kirshner *et al.* (1979) for $B_J \leq 17$ mag.

III. RESULT

We made calculations for a variety of the cosmological parameters in the range of $h = 0.5$–1, $\Omega_0 = 0.03$–1, and $\lambda_0 =$ 0–1.3. In Figure 1 we present the differential number count of galaxies $n(m_\lambda)$ in the $\lambda = B_J$ band in a half-magnitude interval in a unit area of 1 deg^2. To avoid clutter, only a few selected cases are shown in this figure; the parameter choice is (Ω_0, λ_0) = (0.1, 0), (0.1, 0.9), and (1.0, 0) with $h = 0.70$, 1.0, and 0.5 for these three choices, so that t_0 lies between 12.5 and 13.5 Gyr (the dependence of the result on the h is small). For the sake of comparison the no-evolution model prediction is also shown by dashed curves. These model predictions are then compared with the CCD counting by Tyson (1988) for $22 \leq B_J \leq 27$ mag. For brighter magnitudes ($17 \leq B_J \leq 23$ mag) we plotted the photographic number count by Tyson (1988), which agrees with the data of Peterson *et al.* (1979), Jarvis and Tyson (1981), Kron (1980) and Koo (1986) within dex 0.15. For $B_J \leq 17$ mag we took the data from Kirshner *et al.* (1979). To draw our curve we took $z_F = 5$, $\alpha = -1.11$, and $x = 0.2$ and used the UV-SED of early-type galaxies as given by NGC 3379, which represents almost an average of the UV-SED for 31 galaxies explored by Burstein *et al.* (1988). To see the dependence of the

TABLE 1

SENSITIVITY OF THE PREDICTION OF $n(m)$ TO THE CHANGE OF INPUT PARAMETERS

Input Parameter Changes	$\Delta \log n(m)$	
	$B_J = 24$ mag	26 mag
UV-SED (NGC 3379 → NGC 4649)	+0.09	+0.24
$x = 0.2 \to 0$	0	−0.08
$\alpha = -1.11 \to -1.3$	+0.06	+0.06
$z_F = 5 \to 7$	−0.02	−0.10
Local galaxy mix → [Tinsley (1980) mix]	+0.07	+0.08
Estimated overall uncertainty (quadrature)	±0.13	±0.29

NOTE.—Examples are shown for $\Omega_0 = 0.1$, $\lambda_0 = 0$, and $h = 0.7$.

result on the choice of input parameters the calculation is repeated with different parameters and the changes of log $n(m)$ are presented in Table 1. We indicate in Figure 1 the range given in this table for uncertainties of our model calculations.

The first point apparent in this figure is that the prediction of no-evolution models gives $n(m)$ substantially smaller than the observation, as emphasized by Tyson (1988), for all sets of the cosmological parameters. The prediction is dex 0.6 off at $24B_J$ mag for $\Omega_0 = 1$ and dex 0.5 off for $\Omega_0 = 0.1$.

Let us turn to the model with evolution. It is clear that the $\Omega_0 = 1$ model does not agree with the observation; the predicted number $n(m)$, while it agrees up to $23B_J$ mag, rapidly bends off beyond $25B_J$ mag, and $n(m)$ is dex 0.8 smaller at $27B_J$ mag. This effect has already been noted by Yoshii and Peterson (1989) and by Guiderdoni and Rocca-Volmerange (1989), who both concluded that the $\Omega_0 = 1$ universe is not favorable. We found that this feature persists for $\Omega_0 \gtrsim 0.5$ (dex 0.5 off at $27B_J$ mag). An inclusion of the Λ parameter with $\lambda_0 \lesssim 1$ hardly remedies this disagreement. We note that the evolution correction only shifts the curve horizontally, and the maximum number of galaxies at the peak is hardly affected by the correction. Therefore, we conclude that the universe with $\Omega_0 \gtrsim 0.5$ is strongly disfavored at least for modest values of λ_0 ($0 \le \lambda_0 \lesssim 1$).

The prediction of the low-density universe ($\Omega_0 = 0.1$ and 0.03) is slightly off the observation (dex 0.4) at $27B_J$ mag. The shape of the curve is not far from the observed one, however, indicating that a modest modification of the evolution model may fit the observation. A choice of a substantially stronger UV SED (such as that given by NGC 4649) and/or of enhanced UV evolution models ($x \gtrsim 0.5$) bring the prediction in better agreement (<dex 0.2) with the observation. In this case, however, a little upward rise appears in the slope [$dN(m)/dm$] of the predicted curve at around $25B_J$ mag, suggesting that we might overestimate the evolution of ellipticals.

The best agreement with the observation is obtained with a cosmological constant ($\lambda_0 \lesssim 1$) in a low-density model. With our standard choice of parameters, the agreement is achieved within dex 0.1 for $22 \lesssim B_J \lesssim 27$ mag for $\lambda_0 = 0.9$. An agreement within dex 0.1 is achieved also with stronger UV prescriptions. In this case we observe an upward-rise feature again in the predicted curve, however. For a larger Λ ($\lambda_0 \simeq 1.2$, say), this upward-rise feature becomes conspicuous even with a modest UV SED. From the shape of the curve we conclude that $\lambda_0 \simeq 1.2$ is marginally allowed for $\Omega_0 \simeq 0.1$.

We also compared the predicted counts in the R and I bands with the data by Tyson (1988) and others. The agreement between the model prediction and the data is similar to that in the B_J band (except for the counts in the faintest magnitude where the data show a rapid increase), while the highest curves ($\Omega_0 = 0.1$, $\lambda_0 = 0.9$) slightly overshoot the data by dex 0.1 in the R and I bands. We concluded for these bands that the $\Omega_0 = 0.1$ model is consistent with the observation either without or with Λ ($\lambda_0 < 1.2$).

We have then made an analysis for the redshift distribution of galaxies with $20 \lesssim B_J \lesssim 21.5$ mag using the observation by Broadhurst, Ellis, and Shanks (1988). Figure 2 shows the model calculation (normalized to the observed number of galaxies) as compared with their data (the histogram is virtually the same as that in Fig. 3 of Broadhurst *et al.*). While we plotted the whole distribution, we are here particularly concerned with the high redshift behavior which is less affected by their particular sampling properties. The notable feature is that no galaxies are observed with z higher than 0.47 for this magnitude. As already noted by Broadhurst *et al.*, we confirmed that the redshift distribution is generally well reproduced by models without galaxy evolution (a slight deficit is seen for high z in the $\Omega_0 = 1$ model), and cosmological models are not discriminated from the data. If we include evolution as required from the N-m relation, however, the difference in the prediction among different cosmological models becomes amplified. The deficit of high-z galaxies in the $\Omega_0 = 1$ ($\lambda_0 = 0$) model is now quite con-

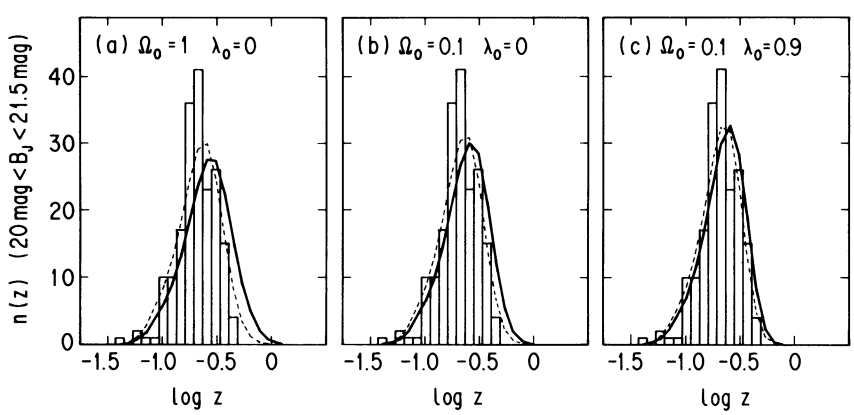

FIG. 2.—Redshift distributions of galaxies in $20 < B_J < 21.5$ mag by Broadhurst *et al.* (1988), as compared with model predictions for three typical choices of parameters. Dashed curves are predictions from the no-evolution model.

TABLE 2

EXPECTED NUMBER OF GALAXIES IN $20 < B_J < 21.5$ mag FOR $z > 0.49$

Ω_0	λ_0	h	t_0(Gyr)	$n(z > 0.49)$	$n(z > 0.49)$ (without evolution)
0.1	0	0.7	12.6	$8.0^{+1.7}_{-2.4}$	$3.0^{+0}_{-1.1}$
0.1	0.9	1.0	12.5	$2.8^{+0.9}_{-1}$	1.4 ± 0.5
1.0	0	0.5	13.0	$16.9^{+5.2}_{-4.6}$	4.9 ± 1.6

NOTE.—The numbers of galaxies are normalized so that the total number agrees with that cataloged in Broadhurst *et al.* 1988. The error shown corresponds to the change of parameters in Table 1.

spicuous. Table 2 summarizes predicted numbers of galaxies for $z > 0.49$. (Our normalization may be uncertain up to 30% by selection effects due to sampling.) Some deficit can also be seen in the ($\Omega_0 = 0.1$, $\lambda_0 = 0$) model. It is interesting to note that stronger UV evolution, which would be required in the *N-m* analysis, makes the deficit of high-z galaxies more pronounced. With a finite cosmological constant $\lambda_0 \gtrsim 0.5$ and $\Omega_0 \simeq 0.1$ the agreement between the prediction and data is optimized, as seen in Figure 2*c*.

IV. CONCLUSION

Predictions of various cosmological models are compared with the recent number of counts of faint galaxies, especially with those by Tyson and the redshift distribution by Broadhurst *et al.* with luminosity evolution incorporated using Arimoto-Yoshii models. We have shown that the model with $\Omega_0 \gtrsim 0.5$ is strongly disfavored either without or with the cosmological constant ($\lambda_0 \lesssim 1$) both from the magnitude number count and the redshift distribution data. The best fit is achieved with the low-density model ($\Omega_0 \lesssim 0.1$) with a cosmological constant ($\lambda_0 \simeq 0.5$–1) for both data. The low-density universe model without cosmological constant does not yield the best fit, but we should probably take it as acceptable in view of uncertainties in the evolution model. It is noteworthy in the model without the cosmological constant, however, that the magnitude number count requires the *UV* evolution stronger than our standard choice, whereas the redshift distribution favors weaker *UV* evolution. It will be an interesting question to ask whether there is an evolution model yielding a better fit to these two data at the same time.[1] It was also shown that an excessively large λ_0 ($\lambda_0 \gtrsim 1.2$ for $\Omega_0 = 0.1$, say) is not favored from the magnitude number count. We note that our analysis was made under the standard assumptions on galaxy evolution and local properties of galaxies. Drastic relaxations of these assumptions might affect the conclusions of the present *Letter*.

We conclude that the current data for the magnitude number count and the redshift distribution strongly favor the low-density universe. The existence of a substantial amount of the cosmological constant is not only allowed, but also even favored by those data. These favored parameter range includes the case $\Omega_0 + \lambda_0 = 1$ as predicted by inflation.

[1] Guiderdoni and Rocca-Volmerange obtained a fit better than ours with a low-density model ($\Lambda = 0$). This is achieved by making the galaxy formation epoch much earlier ($z_F = 30$) than is usually thought and choosing ϕ^* about 3 times larger than our value.

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