The Near-Infrared Galaxy Counts Anomaly: Local Underdensity or Strong Evolution?

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ABSTRACT

We analyze bright-end \((K = 10 - 17)\) galaxy counts from a number of near-infrared galaxy surveys. All studies available as of mid-1997, considered individually or collectively, show that the observed near-infrared galaxy number counts at low magnitudes are inconsistent with a simple no-evolution model. We examine evolutionary effects and a local underdensity model as possible causes of this effect. We find that the data are fit by either a factor of 1.7 - 2.4 deficiency of galaxies out to a redshift of \(z = 0.10 - 0.23\), depending on the k corrections and evolution (e-) corrections used and the adopted values of the Schechter luminosity function parameters, or by unexpectedly strong low redshift evolution in the K-band, leading to \((e+k)\)-corrections at \(z = 0.5\) that are as much as 60% larger than accepted values. The former possibility would imply that the local expansion rate on scales of several hundred Mpc exceeds the global value of \(H_0\) by up to 30% and that the amplitude of very large scale density fluctuations is far larger than expected in any current cosmogetic scenario. The latter possibility would mean that even the apparently most secure aspects of our understanding of galaxy evolution and spectral energy distributions are seriously flawed.

Subject headings: cosmology: miscellaneous — galaxies: evolution — infrared: galaxies — large-scale structure of the universe
1. Introduction

The past ten years have seen a proliferation of near-infrared galaxy surveys providing us with increasingly accurate K-band galaxy counts. The surveys have covered both the bright end (Gardner et al. 1996, Gard96 hereafter; Huang et al. 1997, Huang97 hereafter; Glazebrook et al. 1994; Gardner, Cowie, & Wainscoat 1993; Mobasher, Ellis & Sharples 1986) and faint magnitudes (Moustakas et al. 1997, Djorgovski et al. 1995; McLoed et al. 1995; Soifer et al. 1994; Jenkins & Reid 1991.)

Galaxy counts are an essential tool in the study of galaxy evolution and cosmological geometry. The advantage of near-infrared galaxy counts over optical counts is that the former are much less sensitive to stellar population evolution and the K-band k-corrections are smoother and better understood than in the bluer region of the spectrum. In particular, they are much less affected by bursts of star formation and internal extinction by dust, K-band galaxy counts are therefore the ideal tool for probing large scale density variations.

Huang97 report that the slope of their bright-end galaxy counts is steeper than that predicted by a no-evolution model. The authors dismiss known observational error and evolution as likely causes for this effect and describe a heuristic model with a local deficiency of galaxies by a factor of 2 on scales sizes of around $300 \, h^{-1} \, Mpc$ as a possible cause. But Gard96 find that this model does not fit their galaxy counts.

In this paper, we provide a more in depth study of bright-end galaxy counts in order to determine if other published galaxy counts point to a similar local deficiency of galaxies and to obtain a more precise picture of this underdensity using all K band galaxy counts available as of mid-1997. The possible existence of a very large scale local underdensity merits close scrutiny since it could have profound implications for the determination of $H_0$ (Turner, Cen, & Ostriker, 1992.) We also attempt to quantify the luminosity evolution that would be needed to account for the count slope discrepancy, the most plausible alternative explanation. The data used, models, and best fit methods are described in sections 2, 3, and 4 respectively. Results are presented in section 5 and discussed in section 6.

2. Data

Individual fits were done to the data from Huang97 and Gard96. In order to insure good coverage of the magnitude range under consideration, the rest of the data, listed in Gardner et al. (1993), were combined. Fits with those and with all the data combined were also calculated. The magnitude ranges as well as the total areas covered by the different surveys are listed in Table 1.
A compilation of bright-end number counts is shown in Figure 1a. Density evolution would appear as an excess in the number counts over the no-evolution model. As Figure 1b shows, the slope of the combined low magnitude galaxy counts is indeed steeper than that of the no-evolution model \( d\log(N)/dm = 0.67 \pm 0.01 \), up to \( K = 15 \) compared with the Euclidean value of 0.6.

3. Models

3.1. Galaxy Counts

The expression for the differential number count, the number of galaxies per degree\(^2\) per magnitude as a function of apparent magnitude is (Yoshii & Takahara 1988, hereafter YT88)

\[
N(m) = \int_{0}^{z'} n(m, z) dz \quad (1)
\]

\[
n(m, z) = \frac{\omega}{4\pi} \frac{dV}{dz} \sum_{i=1}^{5} \psi^i(M) ; \quad (2)
\]

where \( \omega \) is the area in steradians. For the near-infrared, the sum over the different galaxy types can be approximated by the Schechter luminosity function (Schechter 1976)

\[
\sum_{i=1}^{5} \psi^i(M) \approx \phi(L)dL
\]

\[
= \phi^*(L/L^*)^\alpha \exp(-L/L^*)d(L/L^*)
= \ln A \phi^* \exp\{-\ln A(\alpha + 1)(M - M^*) - \exp[-\ln A(M - M^*)]\}dM , \quad (3)
\]

from YT88, with \( \ln A = 0.4 \ln 10 \) and

\[
M = m - K(z) - E(z) - 5 \log_{10}(d_L/10pc) , \quad (5)
\]

where \( M, m, K(z) \) and \( E(z) \) are the absolute magnitude, the apparent magnitude, the k-correction and the evolution correction, respectively. The co-moving volume is (YT88)

\[
dV/dz = 4\pi c d_L^2/H_0(1+z)^3\sqrt{1+2q_0z} , \quad (6)
\]

and, in the Friedman model with \( \Lambda = 0 \), the luminosity distance is (YT88)

\[
d_L = \frac{c}{H_0 q_0^2} \{ q_0 z + (q_0 - 1)(\sqrt{1+2q_0 z} - 1) \} , \quad (7)
\]

where \( H_0, q_0, \) and \( c \) are the Hubble constant, the deceleration parameter and the light velocity, respectively.
With $E(z)$ set to zero, this is the no evolution model. The $H_0$ value cancels out in the above equations and $q_0 = 0.5$, except when otherwise indicated. Varying the deceleration parameter does not affect our fits which use counts only up to $K = 17$ where the model is negligibly affected by cosmology.

Normally $z_f \simeq 5$ (YT88) but since we are only using data with $K \leq 17$, we integrate only to $z_f = 1.5$ where we still know the k-correction well (Huang97; Glazebrook et al. 1995.) The redshift distribution of galaxies with $K = 17$ tapers off well before this redshift both observationally (Gardner et al. 1998) and in our model.

Our results are based primarily on Schechter luminosity function parameters calculated by Gardner et al. (1997) ($M^* = -23.12 + 5 \log h$, $\phi^* = 1.66 \times 10^{-2}h^3Mpc^{-3}$ and $\alpha = -0.91$, where $h = H_0/100$.) As alternate possibilities, we consider Mobasher et al. (1993) ($M^* = -23.59 + 5 \log h$, $\phi^* = 0.14 \times 10^{-2}(H_0/50)^3Mpc^{-3}$, and $\alpha = -1.0$) and Glazebrook et al. (1995) ($M^* = -22.75 + 5 \log h$, $\phi^* = 0.026h^3Mpc^{-3}$ and $\alpha = -1.0$) Schechter luminosity function parameters, to test for the sensitivity of our results to these parameters.

K-corrections derived from both the 'UV-hot' elliptical model (Rocca-Volmerange & Guiderdoni 1988) and evolutionary synthesis models (Bruzual & Charlot 1993) are used in our model in order to bracket the range of plausible $K(z)$ terms. We use (e+k)-corrections for $\Omega = 1.0$ and 0.2, computed as a weighted average of the corrections given in Poggianti (1997) for elliptical, Sa and Sc galaxies. The contributions from different Hubble types we use for these 'Averaged' (e+k)-corrections is 30%E /20%Sa /50%Sc (van den Berg et al. 1996.) Similarly averaged (e+k)-corrections calculated by Pozzetti, Bruzual, & Zamorani (1996) for $\Omega \sim 0$ are also used.

In addition, we use (e+k)-corrections for the Hubble type that has the largest such corrections as a conservative limiting case in our fits to obtain a lower limit on the size of the required local underdensity in the presence of evolution. Pozzetti et al. (1996) find elliptical galaxies to have the largest K-band (e+k)-corrections. Poggianti (1997) find Sa galaxies to have only slightly bigger (e+k)-corrections than ellipticals. We therefore use (e+k)-corrections for ellipticals calculated (for $\Omega \sim 0$) by Pozzetti et al. (1996) using a pure luminosity evolution model, and for Sa galaxies calculated (for $\Omega = 1.0$ and 0.2) by Poggianti (1997) using an evolutionary synthesis model (Poggianti & Barbaro 1996.)

### 3.2. Underdensity

In order to introduce a local underdensity in our model, we substituted

$$\phi^* \rightarrow \phi^* D(z) ,$$

(8)
with $D(z)$ taking one of the following two forms: the 'step' underdensity

$$D(z) = \begin{cases} 1.0 - d, & \text{if } z \leq w \\ 1.0, & \text{if } z > w \end{cases},$$  \hspace{1cm} (9)$$

where $d$ and $w$ are the depth and width fit parameters of the underdensity, and the 'smooth' underdensity

$$D(z) = \frac{d}{[d + (1 - d) \exp\{-(z/w)^2\}]},$$  \hspace{1cm} (10)$$

which is a generalization of the underdensity proposed by Huang97 and again $d$, $w$ and $\phi^*$ are fit parameters.

3.3. Strong Evolution

In order to quantify the evolution needed to account for the steep slope if there is no local underdensity, we assume that luminosity evolves as a power of time and substitute the following function into equation (5)

$$E(z) = -a \log_{10}(1 + z),$$  \hspace{1cm} (11)$$

where $a$ is a fit parameter. We also try the following function, assuming that the evolution ceased some time ago,

$$E(z) = \begin{cases} 0.0, & \text{if } z \leq b \\ -a \log_{10}(1 + (z - b)), & \text{if } z > b \end{cases},$$  \hspace{1cm} (12)$$

where $a$ and $b$ are fit parameters.

4. Techniques

4.1. Best Fit Methods

We used two methods to determine the best fit parameters for both the strong evolution and the underdensity models. The first was $\chi^2$ minimization. We simply minimized the usual expression in which we used averaged logarithmic error bars, $\sigma \equiv [\sigma_{\text{upper}} + \sigma_{\text{lower}}]/2$. The logarithm of the galaxy counts and corresponding error bars are used since the latter are more symmetric than the non-logarithmic error bars. This expression unfortunately precludes the use of data points whose error bars overlap zero and information may be lost by averaging the error bars. However, this method does have the advantage of allowing for an estimate of the
goodness-of-fit by looking at the probability that a $\chi^2$ as poor as the value obtained should occur by chance

$$Q = \frac{1}{\Gamma(a)} \int_0^\infty e^{-t^{a-1}} dt,$$

where $a = \frac{\nu}{2}$ with $\nu = \text{number of degrees of freedom}$, and $x = \frac{\chi^2}{2}$. As a rule, $Q \geq 0.1$ indicates a believable goodness-of-fit but when, as will be the case, errors are non-normal, a $Q$ as small as 0.001 is acceptable (Press et al. 1992).

The second fitting method we use is the Poissonian maximum likelihood function which has the form

$$ML = \prod_{i=1}^{n} \frac{\lambda_i^{X_i} \exp(-\lambda_i)}{X_i!},$$

where $X_i \equiv (\text{number count}) \times (\text{area})$ and $\lambda_i \equiv (\text{model number count}) \times (\text{area})$ and the area is that of the survey from which this particular galaxy number count data is taken. We maximize the natural logarithm of equation (14)

$$\log ML = \sum_{i=1}^{n} X_i \log \lambda_i - \sum_{i=1}^{n} \lambda_i - \sum_{i=1}^{n} \log X_i!,$$

The assumption that the errors are well approximated by Poisson statistics holds for the Huang97 data, as the error analysis in that article suggests, as well as for data from the other surveys used in our fits, except at the very faintest magnitudes of the HMWS and HMDS data where uncertainty in star/galaxy separation becomes important (Gardner 1992.)

### 4.2. Error Determination

We use Monte-Carlo simulations to determine the errorbars for our underdensity fits. We generate random Gaussian deviates with zero mean and unit variance and set

$$N(m) = \begin{cases} N_0(m) + \sigma_{\text{lower}} \times RGD, & \text{if } RGD \leq 0.0 \\ N_0(m) + \sigma_{\text{upper}} \times RGD, & \text{if } RGD > 0.0 \end{cases},$$

where $N_0(m)$ is the actual galaxy count from the data and $RGD$ is a random Gaussian deviate. The simulated data sets are then run through the best fit algorithms and the results are used to calculate a variance from the best fit results to the actual data. For the 'step' underdensity model, the errorbars can be expressed as

$$\sigma = \left[ \frac{\sum_{i=1}^{N} (p_0 - p_i)^2}{N} \right]^{1/2}.$$
where $N$ is the number of simulated data sets, $p_0$ and $p_i$ are parameters resulting from the fit to the actual data and simulated data, respectively.

We illustrate the distribution of underdensity values for the 'smooth' underdensity fits by dividing the 2-dimensional $\phi^*D(z)$ - $z$ space into cells and calculating the probability of the simulated data passing through that particular cell. The probability distribution is then plotted as a grey scale plot.

5. Results

The results of the fits using Schechter parameters $M^*$ and $\alpha$ from Gardner et al. (1997) and the 'Step' underdensity described by equation (10) are listed in Table 2. The densities at the center of, and outside the underdensity are $\phi^*_\text{center}$ and $\phi^*_\text{out}$, respectively. The last column shows the percentage difference between these two densities. The 2$\sigma$ error bars (95% confidence level) given in this and subsequent tables were obtained using Monte-Carlo simulations. Only results from the maximum likelihood fits are presented here. Results from best $\chi^2$ fits differ by at most 0.5$\sigma$ for the individual fits (including the fits to 'Other data') and by 0.9$\sigma$ at most for the fits to all the data combined, except for the last eight fits in the table (with the Poggianti (1997) $\Omega = 0.2$ and the Pozzetti et al. (1996) $\Omega \sim 0$ (e+k)-corrections,) where these numbers become 0.9$\sigma$ and 1.3$\sigma$, respectively. The $Q$ values in column 2, are therefore presented only as an indication of the goodness of fit.

For a given k-correction, the results for all the individual data sets (Gard96, Huang97, and 'Other data', for the rest of this discussion) are consistent with each other. Results from most fits to individual data sets differ from the fit to all the data combined by less than 2$\sigma$ and all have $Q > 0.1$. The two fits to the Gard96 data using Poggianti (1997) corrections, however, differ by as much as 2.4$\sigma$ for the $\Omega = 1$ fit and by as much as 5$\sigma$ for the $\Omega = 0.2$ fit. The fits to all the data combined are at least 6$\sigma$ results and have $Q > 0.01$. The results in Table 2 point to a factor of $\sim 2$ deficiency in galaxies out to redshifts of $z = 0.12 - 0.18$.

Only the results from fits to all the data combined are presented here for Schechter parameters $M^*$ and $\alpha$ calculated by Glazebrook et al (1995), in the first half of Table 3, and for those calculated by Mobasher et al (1993), in the second half of Table 3. All the results have $Q > 0.01$ and point to a factor of 1.7 - 2.5 deficiency of galaxies out to redshifts of $z = 0.09 - 0.23$ with at least a 99.99% confidence level.

The fits using limiting cases of published (e+k)-corrections, yielded underdensities that were significant to at least the 5$\sigma$ level. The fits using (e+k)-corrections for Sa galaxies only from Poggianti (1997) yielded a factor of 1.6 - 1.9 deficiency of galaxies out to a redshift of
$z = 0.08 - 0.15$. The underdensities obtained in fits using (e+k)-corrections from Pozzetti et al. (1996) for ellipticals only and $\Omega \sim 0$ had a factor of 1.4 - 2.0 deficiency in galaxies out to $z = 0.11 - 0.24$.

The 'Smooth' Underdensity results for maximum likelihood fits to all the data combined, again for $M^*$ and $\alpha$ calculated by Gardner et al. (1997) are shown as grey scale plots in Figure 3. The darker regions indicate a greater probability of the fit yielding a density profile that passes through that particular point. The probability distribution was calculated from Monte-Carlo simulations as described in section 4.2. The solid lines represent the actual fit to the data. Plots for Bruzual & Charlot (1993), in (a), and Rocca-Volmerange & Guiderdoni (1988), in (b), k-corrections are shown. Plots for the 'Average' Poggianti (1997) (e+k)-corrections for $\Omega = 1.0$ and 0.2 are shown in Figure 3c and 3d, respectively. These fits to all the data combined all have $Q > 0.01$.

The mean redshifts of the redshift distributions for $K = 14.0$ and $K = 17.0$ are $z = 0.095$ and $z = 0.32$ in the absence of k- or evolution corrections and shift to $z = 0.11$ to $z = 0.47$ when (e+k)-corrections (Poggianti 1997) are included. The redshift range involved in the determination of the underdensity parameters is therefore well sampled by the data, regardless of the e- and k-correction used. The width and depth of the underdensity are therefore not uniquely determined by the faintest magnitude bins and it is unlikely that the observed underdensity is in fact an artifact of Malmquist bias. We also tried allowing only $\phi^*$ to vary and not introducing an underdensity. This lead to best fit results with $Q \ll 1.0 \times 10^{-4}$ and maximum likelihood values at least a factor of $10^{22}$ times smaller than those obtained for the underdensity fits.

The evolution model described by equation (11) did not yield satisfactory fits. We tested the model using Schechter parameters determined by Gardner et al. (1997) using both Bruzual & Charlot (1993) and Rocca-Volmerange & Guiderdoni (1988) k-corrections and obtained values of $Q \leq 0.001$ for most fits, indicating a poor goodness-of-fit. Maximum likelihood values were a factor of $10^{4.8} - 10^{84}$ smaller than those obtained in the underdensity fits with the same Schechter parameters and k-corrections.

Substantially better results were obtained for the strong evolution model described by equation (12). The best fits, obtained using the Bruzual & Charlot (1993) k-corrections are shown in Figure 4. However, both Q and maximum likelihood values are again systematically lower (by a factor of $10^{0.8} - 10^{21.4}$ for the maximum likelihood) than those obtained in the underdensity fits. The poorer fits obtained with the evolution models may reflect the fact that the effects of evolution are small at the bright magnitudes, and hence overall low redshifts, that are of interest in modeling the steep slope.
6. Discussion

Turner et al. (1992) found an approximate expression of the correction from the local to global $H_0$, $(\Delta H_0/H_0) = -0.6 \times \Delta n_{gal} \Omega^{0.4}$, where $\Delta n_{gal}$ is the over or under density within the local volume. This would lead, in our case to a local evaluation of $H_0$ that is as much as 30% (for $\Omega \leq 1$) higher than the global value. However the authors warn that the presence of coherent structure with sizes $> 10000$ km/s might lead to a more extreme effect.

Recently, Kim et al. (1997) have shown that $(\Delta H_0/H_0) < 0.10$ if $\Omega_M \leq 1$, using seven supernovae with $0.35 < z < 0.65$. However the authors mention that errors in absolute magnitude calibrations could affect this ratio quite strongly, pointing to the 0.09 mag difference between the absolute magnitude calibrations used in their paper and by Riess, Press, & Kirshner (1996) which could lead to a ratio of $(\Delta H_0/H_0) < 0.21$. The possibility that the local and the global values of $H_0$ differ by of order 20% cannot yet be ruled out directly.

Zehavi et al. (1998) have analyzed the peculiar velocities of 44 Type Ia supernovae and found a deviation from the Hubble law consistent with a void of $\sim 20\%$ underdensity surrounded by a dense wall at $70h^{-1}Mpc$. This result is consistent with those obtained from peculiar motions of rich clusters (Lauer & Postman 1992; Lauer et al. 1997) but cannot be used to explain the steep slope of near-infrared galaxy count. With this small local void introduced in our model, our underdensity fits yield voids that are at most a factor of 1.15 smaller in extent, but as much as 1.25 times more deficient in galaxies, than those listed in Tables 2 and 3.

However, Wang, Spergel, & Turner (1998) used current knowledge of CMB anisotropies to show that a variation of a few percent between available measurements of $H_0$ and its true global value should be expected and that a variation as large as 10% would be possible for surveys with diameter $200h^{-1}Mpc$. For larger surveys scales, not much variation is expected. For example, for a survey with a $500h^{-1}Mpc$ radius, variations of at most 2% in expansion parameter and 13% in density are expected at the 95% confidence level. This would seem to mitigate against the large scale underdensity found by our fits if current cosmogonic theories are at least roughly valid.

The goodness of fit ($Q > 0.01$) and maximum likelihoods values obtained with the second evolution model presented in section 3.3 seem to indicate that this is a viable alternative to the underdensity models. However, as we can see in Figure 4, our fit results show more evolution than can be accounted for by present evolution calculations. In fact, the (e+k)-correction from the fits is as much as 56% stronger than that of the 'Averaged' (e+k)-corrections for $\Omega = 0.2$ used in our underdensity fits (for example, at $z = 0.5$, $\Delta M_{(e+k)} = -1.12$ compared with $-0.74$) and 34% stronger than even the (e+k)-corrections for Sa galaxies alone (again for $\Omega = 0.2$).
which we took to represent an upper limit on the evolution (and for which $\Delta M_{(e+k)} = -0.91$ at $z = 0.5$.)

A more careful consideration of evolution as a source of the effect noticed by Huang97 and confirmed by our fits for all the data is necessary since our understanding of galaxy evolution is still incomplete. The recent publication of an extensive data base for Galaxy Evolution Modeling (Leitherer et al. 1996) might lead to larger (e+k)-corrections in the near-infrared. A model including both evolution and an underdensity might prove to be a more acceptable solution than either one alone, but cannot yet be studied with the data presently available. Redshift surveys should ultimately answer the question of whether or not a large region of the local universe is underdense.

However, for the present, the K-band galaxy counts pose a significant puzzle: unless several independent determinations are giving similar but incorrect results, we must confront the possibility of either a cosmic density fluctuation of entirely unanticipated scale and amplitude or a serious deficiency in the best understood features of galaxy evolution and spectral energy distributions (or, of course, some combination of the two).

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Figure Captions

Figure 1. (a) Compilation of bright end near-infrared galaxy counts taken from Gardner et al. (1996), Huang et al. (1997) and the Gardner et al. (1993) compilation (number counts for Glazebrook et al. (1994) and Mobasher et al. (1986) are listed in this paper as well.) The solid line represents the actual slope of the combined galaxy counts up to $K = 15$ and the dotted line shows the Euclidean slope. (b) Same as (a), with the Euclidean slope $d \log(n)/dm = 0.6$ scaled out and only points with fractional error $\leq 0.5$ and $K \leq 15$ plotted.

Figure 2. ‘Smooth’ underdensity fit results for all the data using $M^* = -23.12 + 5 \log h$ and $\alpha = -0.91$ and (a) Bruzual & Charlot (1993) k-corrections, (b) Rocca-Volmerange & Guiderdoni (1988) k-corrections and averaged (e+k)-corrections from Poggianti (1997) for (c) $\Omega = 1.0$ and (d) $\Omega = 0.2$. Darker regions indicate a greater probability of the fit yielding a density profile that passes through that particular point. The solid lines represent the best fit to the data.

Figure 3. Evolution best fit results with $M^* = -23.12 + 5 \log h$, $\alpha = -0.91$, Bruzual & Charlot (1993) and Rocca-Volmerange & Guiderdoni (1988) k-corrections (shown in solid line and labeled $K(z)_{BC}$ and $K(z)_{RG}$, respectively.) The Average and Sa (e+k)-corrections from Poggianti (1997) are also shown. The corresponding $\Omega$ is indicated on the right.
| Survey               | Range        | Area          |
|---------------------|--------------|---------------|
| Gardner et al. 1996 | 10.25 to 15.75 | 9.84 degree$^2$ |
| Huang et al. 1997   | 11.25 to 14.50 | 9.81 degree$^2$ |
|                     | 14.75 to 16.00 | 8.23 degree$^2$ |
| Other data $^c$     |              |               |
| HWS                 | 10.50 to 14.50 | 1.58 degree$^2$ |
| HMWS                | 12.75 to 16.75 | 582.01 arcmin$^2$ |
| HMDS                | 13.75 to 18.75 | 167.68 arcmin$^2$ |
| Glazebrook et al. 1994 | 13.50 to 16.50 | 551.90 arcmin$^2$ |
| Mobasher et al. 1986 | 10.25 to 12.25 | 41.56 degree$^2$ |

$^a$ of data in $K$ magnitude

$^b$ Total area covered for $K \leq 17$

$^c$ Listed in Gardner et al. 1993
Table 2. Results of 'Step' Underdensity Fit ($M^* = -23.12 + 5 \log h, \alpha = -0.91$)

| Survey                | Q/ln $ML$ | $\phi^*_{center} (\times 10^{-2})$ | $\phi^*_{out} (\times 10^{-2})$ | Width (z) | $\Delta n_{gal}$ (in %) |
|-----------------------|-----------|------------------------------------|---------------------------------|------------|-------------------------|
| Bruzual & Charlot K-corrections |           |                                    |                                 |            |                         |
| Gardner et al.        | 0.614/-39.20 | 1.82 ± 0.58                       | 3.06 ± 0.76                     | 0.220 ± 0.083 | 40.5 ± 11.8             |
| Huang et al.          | 0.32/-76.58 | 1.40 ± 0.41                       | 2.90 ± 0.33                     | 0.146 ± 0.044 | 51.6 ± 13.2             |
| Other data a          | 0.288/-109.06 | 1.20 ± 0.54                      | 2.71 ± 0.54                     | 0.188 ± 0.058 | 55.6 ± 18.0             |
| All data              | 0.0704/-265.38 | 1.48 ± 0.23                     | 2.87 ± 0.20                     | 0.156 ± 0.032 | 48.5 ± 7.4             |
| Rocca-Volmerange & Guiderdoni K-corrections |           |                                    |                                 |            |                         |
| Gardner et al.        | 0.462/-40.61 | 1.46 ± 0.50                      | 2.70 ± 0.68                     | 0.259 ± 0.102 | 45.9 ± 12.8             |
| Huang et al.          | 0.354/-75.63 | 1.13 ± 0.35                      | 2.43 ± 0.31                     | 0.170 ± 0.058 | 53.6 ± 13.3             |
| Other data            | 0.274/-109.40 | 1.02 ± 0.47                      | 2.32 ± 0.44                     | 0.221 ± 0.038 | 56.2 ± 18.4             |
| All data              | 0.0803/-262.85 | 1.21 ± 0.18                      | 2.42 ± 0.20                     | 0.183 ± 0.038 | 49.9 ± 6.6              |
| Poggianti E+K-corrections (\(\Omega = 1\)) |           |                                    |                                 |            |                         |
| Gardner et al.        | 0.658/-38.87 | 1.82 ± 0.39                      | 2.96 ± 0.42                     | 0.190 ± 0.050 | 38.6 ± 9.72             |
| Huang et al.          | 0.354/-75.63 | 1.30 ± 0.55                      | 2.87 ± 0.38                     | 0.124 ± 0.062 | 54.7 ± 18.2             |
| Other data            | 0.250/-109.82 | 1.20 ± 0.53                      | 2.51 ± 0.45                     | 0.162 ± 0.082 | 52.1 ± 19.1             |
| All data              | 0.0267/-280.74 | 1.42 ± 0.27                      | 2.84 ± 0.22                     | 0.134 ± 0.041 | 50.2 ± 8.7              |
| Poggianti E+K-corrections (\(\Omega = 0.2\)) |           |                                    |                                 |            |                         |
| Gardner et al.        | 0.649/-38.93 | 1.82 ± 0.33                      | 2.84 ± 0.28                     | 0.180 ± 0.018 | 35.7 ± 9.8              |
| Huang et al.          | 0.108/-92.45 | 1.27 ± 0.47                      | 2.76 ± 0.30                     | 0.116 ± 0.033 | 54.0 ± 16.1             |
| Other data            | 0.237/-110.08 | 1.20 ± 0.55                      | 2.35 ± 0.47                     | 0.151 ± 0.112 | 48.9 ± 21.0             |
| All data              | 0.0186/-285.56 | 1.40 ± 0.21                      | 2.73 ± 0.17                     | 0.124 ± 0.022 | 48.5 ± 7.14             |
| Pozzetti et al. E+K-corrections (\(\Omega \sim 0\)) |           |                                    |                                 |            |                         |
| Gardner et al.        | 0.628/-39.13 | 1.86 ± 0.42                      | 3.52 ± 1.12                     | 0.223 ± 0.108 | 47.3 ± 16.5             |
| Huang et al.          | 0.353/-77.73 | 1.44 ± 0.23                      | 3.25 ± 0.34                     | 0.157 ± 0.016 | 55.6 ± 13.4             |
| Other data            | 0.292/-108.9 | 1.23 ± 0.34                      | 3.11 ± 0.69                     | 0.194 ± 0.037 | 60.4 ± 19.8             |
| All data              | 0.0744/-266.1 | 1.52 ± 0.10                      | 3.08 ± 0.18                     | 0.154 ± 0.017 | 50.6 ± 6.1              |

aListed in Table 1
Table 3. Results of ‘Step’ Underdensity Fit for all data combined using other $M^*$ and $\alpha$

| K(z) & E(z) | Q/\ln ML | $\phi_{\text{center}}(\times10^{-2})$ | $\phi_{\text{out}}(\times10^{-2})$ | Width ($z$) | $\Delta n_{\text{gal}}$ (in %) |
|-----------|-----------|-------------------------------------|-----------------------------------|-------------|---------------------------------|
| (1)       | 0.0444/-274.08 | 2.40 ± 0.39 | 4.25 ± 0.29 | 0.104 ± 0.030 | 43.6 ± 8.4 |
| (2)       | 0.0509/-271.13 | 2.07 ± 0.28 | 3.54 ± 0.18 | 0.132 ± 0.009 | 41.6 ± 7.2 |
| (3)       | 0.0186/-285.63 | 2.36 ± 0.44 | 4.41 ± 0.34 | 0.099 ± 0.033 | 46.6 ± 9.1 |
| (4)       | 0.0131/-290.23 | 2.33 ± 0.37 | 4.29 ± 0.24 | 0.093 ± 0.016 | 45.8 ± 8.1 |
| (5)       | 0.0542/-268.5  | 2.49 ± 0.28 | 4.64 ± 0.72 | 0.115 ± 0.067 | 46.3 ± 8.7 |
|           |             |           |           |           |                   |
|           | $M^* = -22.75 + 5 \log h, \alpha = -1.0$ \textsuperscript{b} | | | | |
| (1)       | 0.0701/-266.36 | 0.768 ± 0.160 | 1.77 ± 0.25 | 0.204 ± 0.069 | 56.7 ± 6.6 |
| (2)       | 0.0938/-261.73 | 0.624 ± 0.115 | 1.52 ± 0.17 | 0.233 ± 0.054 | 58.9 ± 6.0 |
| (3)       | 0.0300/-279.10 | 0.750 ± 0.111 | 1.64 ± 0.11 | 0.171 ± 0.027 | 54.4 ± 6.1 |
| (4)       | 0.0187/-285.28 | 0.741 ± 0.111 | 1.55 ± 0.10 | 0.156 ± 0.025 | 52.3 ± 6.7 |
| (5)       | 0.0690/-267.13 | 0.814 ± 0.096 | 2.07 ± 0.33 | 0.218 ± 0.049 | 60.7 ± 6.9 |

\textsuperscript{a}from (1) Bruzual & Charlot 1993, (2) Rocca-Volmerange & Guiderdoni 1988, (3) Poggianti 1997 $\Omega = 1.0$ and (4) $\Omega = 0.2$, (5) Pozzetti et al. 1996

\textsuperscript{b}Glazebrook et al. 1995

\textsuperscript{c}Mobasher et al. 1993
Gardner et al. (Q = 0.504)
Huang et al. (Q = 0.0106)
Other data (Q = 0.0520)

- All data (Q = 8.79 \times 10^{-4})
- Other data (Q = 0.0520)
- Huang et al. (Q = 0.0106)
- Gardner et al. (Q = 0.504)