Counter-Evolution of Faint Field Galaxies\textsuperscript{1}

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Abstract

We adopt a new approach to explore the puzzling nature of faint blue field galaxies. Instead of assuming that the local luminosity function is well defined, we first determine whether any non-evolving set of luminosity functions for different spectral types of galaxies is compatible with the observed marginal distributions in optical and near-infrared counts, $B - R$ colors, and redshifts. Exploiting a non-negative least squares method, we derive a new no-evolution model that is found to fit all the observations surprisingly well, from $B \leq 15$ to the limit of $B \sim 24$ for redshifts and $B \sim 26$ for colors and counts. Contrary to previous conclusions, the faint galaxies in excess of our new non-evolutionary model are red rather than blue. Although our fits are far better than previous no-evolution models, the remaining deviations from the observations still suggest the need for some, but slight, evolutionary component or model revisions. We conclude that models more exotic than mild luminosity evolution, such as those requiring rapid evolution in star formation rates, disappearing dwarf galaxy populations, high values of the cosmological constant, rapid mergers, or substantial non-conservation of galaxy numbers with time, are no longer as compelling. Our results resurrect field galaxies as promising probes of the curvature of space.

Subject headings: galaxies: evolution — galaxies: luminosity function, mass function — galaxies: photometry — cosmology: observations
1. Introduction

For over a decade, the steep slope of the faint field galaxy counts and their very blue colors have been explained as the result of mild evolution in the spectral energy distributions (SED’s) of galaxies. The excess of counts above non-evolutionary (NE) models has been claimed to be a factor of two by $B \sim 20$ (Maddox et al. 1990, Loveday et al. 1992) or by $B \sim 22.5$ (Colless et al. 1990), and even factors of 5 to 15 by $B \sim 25$ (Tyson 1988). These blue counts have been claimed, even with evolution, to be incompatible with a flat ($\Omega = 1$) Friedmann universe (Koo 1990, Guiderdoni and Rocca-Volmerange 1990) or with the observed near-infrared K band counts (Cowie et al. 1993). Yet recent redshift surveys show that galaxies fainter than 20th mag exhibit redshift distributions close to that predicted by NE models (Broadhurst et al. 1988, Colless et al. 1990, Lilly et al. 1991).

A commonly held belief is that dramatic revisions to the conventional view are needed. Some have revised the cosmology by adopting a non-zero cosmological constant, $\Lambda$ (Fukugita et al. 1990). Others have proposed non-conservation of galaxy numbers, due to mergers (White 1989, Cowie et al. 1991, Broadhurst et al. 1992), a disappearing population of dwarf galaxies (Cowie et al. 1991, Babul and Rees 1992), or dwarfs which have faded substantially in recent times (Broadhurst et al. 1988).

An alternative view is that the uncertainties of local and distant field galaxy data and galaxy models preclude a convincing case for any exotic theories at this time. Instead, a NE model generated by trial and error adjustments of galaxy luminosity functions (LF’s) versus color is claimed to provide moderately good fits to the known data (Koo and Kron 1992). In this letter, we adopt a new objective method to answer the question: what is the best fit that any NE model can ever hope to make to the observations?

2. Observations and Method

Our method of fitting a model to the data is conceptually simple. The goal is to solve for the weights to be applied to a set of input basis vectors that best fit (using non-negative least squares) the observations. Our technique is similar to that used to derive the stellar components of a composite galaxy spectrum in population synthesis studies (e.g. Faber 1972). Rather than the spectra for stars used in population synthesis, the input vectors in our current analysis are the predicted number distributions of colors and redshifts for 154 combinations of galaxy absolute luminosities and color-classes. Fourteen absolute
magnitude bins were chosen, each extending from a bright limit to a faint limit of $M_{B_J} = -11$ (i.e., the first bin is one magnitude wide extending from $M_{B_J} = -12$ to -11, the next is two magnitudes wide extending from $M_{B_J} = -13$ to -11, and so on). Bins were chosen in this way to ensure that the different LF’s were both monotonically increasing and smooth (dropping these constraints did not significantly improve the fits). An open universe with $q_0 = 0.05$ and a Hubble constant of 50 km-sec$^{-1}$-Mpc$^{-1}$ is adopted for the model predictions. Eleven color classes of galaxies were chosen, ranging from very red to very blue (see Table 1). Recently revised Bruzual models (Bruzual and Charlot 1993) were used to create the SED’s. For NE, the SED’s, i.e. luminosities and colors, of the galaxies are assumed to be independent of time. The output weights for these 154 kinds of galaxies are proportional to their volume densities, and thus provide a direct measure of the LF for each color-class of galaxy.

Instead of the galaxy spectrum used in population synthesis, the data to be fit in this study is organized as a vector matched to the model input vectors and consists of the observed galaxy counts (in $K$, $r$, and $B_J$) as well as color and redshift distributions. The color data were binned in 0.1 mag of $B_J - R_F$ and ranged from $B \sim 19$ to 27 at one magnitude intervals. The redshift data ranged from $B \sim 15$ to 24, also at one magnitude intervals, but binned in 1.0 units of 7 log z. Each color or redshift distribution was normalized to the observed $B_J$ counts. These observations, along with their attendant problems of zero-points for the colors and incompleteness for the redshifts, are from the compilations of Koo and Kron (1992), except for the recent redshifts of Colless et al. (1993) for $B = 23$ to 24. Though inclusion of observational errors are important at some level, they were largely ignored. The results also depend on the relative weights adopted for different parts of the data set. As a default, we have used weights which are proportional to the observed number of galaxies in each bin. However, in order to de-emphasize the importance of the number counts we fit to the number of galaxies per 0.1 square degrees instead of per 1 square degree. In addition, we have weighted the redshift distributions by 5 times the observed numbers in each bin to increase the importance of the observed redshift distributions relative to the color distributions.

In mathematical terms, given an $m \times n$ matrix, $P$, and an $m$-vector, $D$, we wish to compute the $n$-vector, $X$, which solves the least squares problem, $PX = D$, subject to $X_i \geq 0$ for all $i$. The data vector, $D$, is filled by the tables of observational data. The $i$th-column of the prediction matrix, $P$, is an input vector filled by the model-generated table of data for each kind of galaxy, $i$. The output vector, $X_i$, represents the number per unit volume assigned to the $i$th kind of galaxy in the least-squares solution.
3. Results and Discussion

Table 2 provides the resultant LF for each of the Bruzual color classes. Figure 1 compares various color-integrated LF’s to some other recent derivations. Our total LF to $M_{B_J} \sim -18$ is seen to be a good match to the flat local LF derived by Loveday et al. (1992). Though our predicted rise appears inconsistent with the faintest two points of the Loveday et al. LF, Figure 1 shows that this steepening is compatible with recent LF’s derived from fainter redshift surveys, including the local LF derived by Eales (1993) and the faint field ($B_J > 20$) LF derived by Lonsdale and Chokshi (1993). Our LF’s divided by color can be directly compared to those adopted by Metcalfe et al. (1991); our LF when summed over the same color intervals of $B-V$ (see Figure 1) also show a steep low-luminosity rise for the blue galaxies and consistent normalizations brighter than the valid limits of the Metcalfe et al. (1991) fits.

Using these LF’s, the predicted NE counts, colors, and redshift distributions are compared to existing observations and displayed in Figures 2 to 4, respectively. The fits are remarkably good and considerably improved over the hand-made NE model of Koo and Kron (1992). Though not shown, we also checked that the color-redshift distributions are also consistent, since in principle, different correlations of color-redshift may result in the same color or redshift marginal distribution. Our new NE model shows only a slight deficit (less than a factor of two) of blue counts compared to the observations, even to the faintest reliable limits of $B \sim 25$. The fit to the red ($r$) counts is excellent and the fit to the near-infrared ($K$) counts is acceptable. The spectral energy distributions predict $V-K$ colors for elliptical galaxies that are too blue by approximately 0.3 mag compared to observations (see Fig. 11, Bruzual and Charlot 1993). A shift of 0.3 mag towards brighter magnitudes in K for the fit to the K-band counts would actually improve the fit. The color distributions are also very well matched from $B \sim 19$ to 25. It is intriguing to note that the comparison of the color distributions to the NE model shows that the excess faint galaxies are redder than average, not bluer, contrary to standard lore based on previous NE models. The match to the redshift distributions is generally not as good fainter than about 21st mag, beyond which the predictions yield more low redshift $z < 0.1$ (i.e. local low-luminosity dwarfs with $M_B \sim -12$ to $-17$) galaxies than observed, typically by about 10% of the total sample. Whether this slight discrepancy can be explained by selection effects against compact or low surface-brightness dwarfs in the observations, by systematic errors in the zero-points of the faintest color data, or by the limitations of our model remains to be explored. For $B = 23$ to 24, our new NE model predicts that about 33% of the galaxies will have redshifts $z \geq 0.7$. This is greater than the 15% observed in the most recent data of Colless et al. (1993), but not at a high level of statistical significance given the sparse
redshift sample at these very faint magnitudes.

Despite the success of our near-optimal NE model, we are not arguing against some evolution. To the extent that the observed data are all accurate and our SED’s are representative of real galaxies, our experiment indicates that no NE model exists that will fit the observations totally, especially the higher (by \(\sim 40\%\)) counts by \(B_J \sim 24\). Whether these discrepancies can be explained by improved data and/or various evolutionary models will be explored in future papers along with more detailed error analysis and multicolor data.

Since our NE model is able to fit the counts, colors, and redshifts so well over a large range in magnitude, we explored why previous models predict fewer faint galaxies and redder colors. Most assumed one-to-one conversions of galaxy morphology to color rather than including a dispersion of colors for each galaxy type; this assumption naturally results in too many red galaxies compared to reality. Others adopted a single LF shape for all galaxy types; with a standard Schechter LF, e.g., the blue galaxies tend to be underestimated at the extremes of the LF. Many models of the bluest galaxies included a characteristic luminosity for either a Schechter or Gaussian LF that was fainter than that for redder galaxies; this tends to underestimate the number of luminous blue galaxies, which are known to exist locally (specific examples can be found in the study of Markarian galaxies by Huchra 1977). Some models even had the bluest galaxies as those with constant star-formation rate and thus \(B - V \sim 0.45 - 0.55\); many galaxies are bluer (again, see Huchra 1977).

In conclusion, we confirm our contrarian view from Koo and Kron (1992) that exotic theories are not yet required to explain existing faint field galaxy data. Instead, we suggest that the local LF’s for different color classes of galaxies adopted by previous studies are likely to be significantly in error. We derive a plausible set of LF’s by an objective technique. The resulting NE predictions match well enough to the observations so that adoption of mild luminosity evolution remains a viable path to improved fits. Since the observational evidence for non-conservation of galaxy numbers with recent lookback time is now far less compelling, distant field galaxies may be resurrected as promising probes of the curvature of space.

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### TABLE 1
INPUT GALAXY MODELS

| Model | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 |
|-------|----|----|----|----|----|----|----|----|----|----|----|
| Age\(^{(a)}\) | 0.4 | 2.0 | 6.8 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 16.0 | 20.0 |
| \(\mu\)^{(b)} | C  | C  | C  | 0.01 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.70 | B  |
| \(B - V\) | 0.15 | 0.25 | 0.35 | 0.43 | 0.52 | 0.61 | 0.70 | 0.78 | 0.85 | 0.95 | 0.99 |
| \(B_J - R_F\) | 0.26 | 0.38 | 0.49 | 0.59 | 0.69 | 0.78 | 0.87 | 0.96 | 1.02 | 1.13 | 1.17 |

\(^{(a)}\) Age of the galaxy model in Gyr.

\(^{(b)}\) Star formation history of the galaxy model: All models have Salpeter initial mass functions for masses between 0.1 and 125 \(M_\odot\). Models 1-3 have a constant (C) star formation rate. Models 4-10 have an exponentially decreasing star formation rate parameterized by \(\mu\), where \(\mu\) is the fraction of mass converted into stars in 1 Gyr. Model 11 is a \(10^7\) Gyr burst (B) of star formation.
### TABLE 2
OUTPUT MODEL LUMINOSITY FUNCTIONS

\( \text{LOG } \Phi \text{ (Number/mag/Mpc}^3) \)

| Model | \( M_{BJ}^{(b)} \) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | Total | Obs.\(^{(c)}\) |
|-------|------------------|----|----|----|----|----|----|----|----|----|----|----|-------|----------------|
| -24.5 | -8.72            |    |    |    |    |    |    |    |    |    |    |    | -8.72 | -10.8 |
| -23.5 | -6.66            | -7.05 | -7.07 | -6.32 | -8.72 |    |    |    |    |    |    |    | -6.06 | -6.32 |
| -22.5 | -6.66            | -7.05 | -4.74 | -5.04 | -8.72 |    |    |    |    |    |    |    | -4.56 | -4.35 |
| -21.5 | -5.40            | -4.64 | -4.51 | -4.12 | -7.05 | -3.93 | -4.07 | -4.30 |    |    |    |    | -3.41 | -3.46 |
| -20.5 | -3.75            | -4.64 | -3.97 | -3.37 | -4.34 | -3.93 | -4.07 | -4.30 | -3.67 | -2.90 | -3.07 |    |       |       |
| -19.5 | -3.59            | -4.64 | -3.97 | -3.37 | -3.49 | -3.93 | -4.01 | -4.06 | -3.34 | -2.72 | -2.92 |    |       |       |
| -18.5 | -3.59            | -4.64 | -3.97 | -3.37 | -3.49 | -3.27 | -4.01 | -4.06 | -2.99 | -2.54 | -2.87 |    |       |       |
| -17.5 | -3.59            | -4.64 | -3.97 | -3.37 | -3.49 | -3.27 | -4.01 | -4.06 | -2.84 | -2.48 | -2.85 |    |       |       |
| -16.5 | -3.59            | -4.64 | -3.97 | -3.37 | -3.49 | -3.27 | -4.01 | -4.06 | -2.32 | -2.18 | -2.85\(^{(d)}\) |    |       |       |
| -15.5 | -3.59            | -4.64 | -3.97 | -3.37 | -3.49 | -3.27 | -4.01 | -4.06 | -2.04 | -1.96 | -2.86 |    |       |       |
| -14.5 | -2.24            | -4.64 | -3.97 | -1.75 | -3.49 | -3.27 | -4.01 | -4.06 | -2.04 | -1.47 | -2.87 |    |       |       |
| -13.5 | -2.24            | -4.64 | -1.14 | -1.75 | -3.49 | -3.27 | -4.01 | -4.06 | -2.04 | -0.97 | -2.88 |    |       |       |
| -12.5 | -2.24            | -4.64 | -0.62 | -1.75 | -3.49 | -3.27 | -4.01 | -4.06 | -2.04 | -0.57 | -2.89 |    |       |       |
| -11.5 | -2.24            | -4.64 | -0.10 | -1.75 | -3.49 | -3.27 | -4.01 | -4.06 | -2.04 | -0.08 | -2.91 |    |       |       |

\(^{a}\) \( H_o=50 \text{ km s}^{-1} \cdot \text{Mpc}^{-1} \)

\(^{b}\) Center of one magnitude bins

\(^{c}\) Luminosity function from Loveday et al. (1992): \( M^* = -21, \alpha = -0.97 \)

\(^{d}\) Loveday et al. luminosity function only valid for \( M_{BJ} \leq -16.75 \)
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Figure Captions

**FIG. 1a.** - Derived luminosity functions versus previously derived ones, all scaled to $H_0 = 50$ km-sec$^{-1}$-Mpc$^{-1}$. Thick-lined histogram is the derived total differential luminosity function; thin line is from the derived Schechter LF of Loveday et al. (1992) and is valid for $M_{B_J} \leq -16.75$ (dashed line indicates extrapolation of this fit). Circles are data points from Loveday et al. (1992), plus signs from Eales (1993), and stars from Lonsdale and Chokshi (1993). For clarity, we have not included the authors’ original error bars on these points.

**FIG. 1b.** - Same as for 1a, except thick-lined histogram applies for color classes with $B - V \geq 0.85$. The thin line is the differential LF from Table 8 of Metcalfe et al. (1991) for the same color range and valid for $M_{B_J} \leq -17.5$; dashed line indicates extrapolation of their fit.

**FIG. 1c.** - Same as for 1b except for $0.6 < B - V < 0.85$ and thin line being valid for $M_{B_J} \leq -15.5$; dashed line indicates extrapolation of their fit.

**FIG. 1d.** - Same as for 1c except for $B - V \leq 0.6$.

**FIG. 2.** - Log of the differential counts $A$ (per mag per square degree) of faint field galaxies versus magnitude in the indicated bands. The $B_J$ and Gunn $r$ band observations (symbols) are compilations of data made by Koo and Kron (1992); the infrared $K$ band counts are a compilation from Gardner et al. (1993). Our new no-evolution predictions are shown as curves.

**FIG. 3.** - Color ($B_J - R_F$) distributions versus indicated magnitude intervals are shown as thick lines for the observations and thin lines for the model predictions. The observations are compilations (Koo and Kron 1992) from the data of several groups.

**FIG. 4.** - Normalized histograms versus redshift (log $z$) for magnitude ($B_J$) intervals as indicated. Bin size is 0.143, since original bin size was 1.0 in $7\log z$. The model predictions are shown as thin lines; observations shown as thick lines are compilations from different surveys (Koo and Kron 1992); the $B_J = 23$ to 24 observations are updated from Colless et al. (1993).
