PASSIVE EVOLUTION: ARE THE FAINT BLUE GALAXY COUNTS PRODUCED BY A POPULATION OF ETERNALLY YOUNG GALAXIES?

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ABSTRACT

A constant-age population of blue galaxies, postulated in the model of Gronwall & Koo, seems to provide an attractive explanation of the excess of very blue galaxies in the deep galaxy counts. Such a population may be generated by a set of galaxies with cycling star formation rates or, at the other extreme, be maintained by the continual formation of new galaxies that fade after they reach the age specified in the Gronwall & Koo model. For both of these hypotheses, we have calculated the luminosity functions, including the respective selection criteria, the redshift distributions, and the number counts in the $B$, $V$, and $K$ bands. We find a substantial excess in the number of galaxies at low redshift ($0 < z < 0.05$) over that observed in the Canada-France-Hawaii redshift survey (Lilly et al.) and at the faint end of the Las Campanas luminosity function (Lin et al.). Passive or mild evolution fails to account for the deep galaxy counts because of the implications for low-redshift determinations of the I-selected redshift distribution and the r-selected luminosity function in samples where the faded counterparts of the star-forming galaxies would be detectable.

Subject headings: galaxies: evolution — galaxies: luminosity function, mass function — galaxies: photometry

1. INTRODUCTION

That the deep galaxy counts require an extensive blue population of faint galaxies is undisputed. A variety of different models invoke large-scale merging or new galactic populations to explain this excess. Others claim that this excess can be explained simply with mild (essentially passive) evolution, and that the introduction of merging and new populations is unnecessary (e.g., Gronwall & Koo 1995, hereafter GK; Pozzetti, Bruzual, & Zamorani 1996). In particular, GK provide an attractive explanation of the deep galaxy counts by determining the local luminosity functions (LFs) for galaxies in 11 different morphological classes so as to also fit the galaxy redshift distributions and broadband colors. For eight of the 11 morphological classes, GK allow the luminosities and colors of the galaxies to evolve in a way that is consistent with the construction of their morphological classes. GK require that the remaining three classes be very blue and completely nonevolving. Maintaining this population of blue galaxies requires either the continual formation of blue galaxies, in which case a remnant of fading galaxies would be left, or a cycling star formation rate in these galaxies, in which case the colors would not seem to be the same unless there was a significant amount of time between bursts (Babul & Ferguson 1996). In this Letter we impose the aforementioned physical interpretations on the nonphysical blue galaxies in the GK model, and we assess their credibility.

2. RESULTS

In our physical interpretations of the GK model, we maintain GK's population of nonphysical blue galaxies from $z = 0$ to $z = 1$. We believe that $z = 1$ is early enough to account for the predominance of blue galaxies seen at faint magnitudes—which the GK model attempts to explain with a population of nonphysical blue galaxies—but not so early as to produce an unreasonably high number of faded galaxies. We interspersed periods of constant star formation of duration equal to that given by GK for the nonphysical blue galaxies with periods of no star formation. If the $B - V$ colors specified for the nonphysical blue galaxies in the GK model are not to be more than 0.10 mag different from the colors specified in the GK model during the active star formation phase, we find that the periods of no star formation have to be at least 1.2 Gyr for GK’s bluest morphological type and 2.0 Gyr for GK’s second-bluest morphological type.

We consider four models, which bear out a range of different physical interpretations of the GK models. In model A, the bluest class of galaxies, corresponding to class 1 of the GK model, undergoes a period of constant star formation for 0.4 Gyr, followed by a 1.2 Gyr period with no star formation, and repeats this cycle indefinitely. The second-bluest class of galaxies, corresponding to class 2 of the GK model, undergoes a period of constant star formation for 2 Gyr followed by a 2 Gyr period with no star formation, and again repeats this cycle indefinitely. Models B, C, and D are similar to model A, except that the bluest class of galaxies have 2.4 Gyr, 4.8 Gyr, and an infinite period of time, respectively, separating the bursts of star formations, and the second-bluest class of galaxies have 6 Gyr, 12 Gyr, and an infinite period of time, respectively, separating the bursts of star formation. To maintain this constant population of young blue galaxies in the GK model, we employed several sets of these galaxies with the star formation timed so that exactly one set of these galaxies would be undergoing their burst of constant star formation at any given time. Obviously, in models where galaxies cycle more frequently, a much smaller set of galaxies is required, and in models where galaxies cycle less frequently, a much larger set of galaxies is required, to maintain this population of very blue...
galaxies. We assumed a Salpeter (1955) initial mass function (IMF) with upper and lower mass limits of 0.1 and 125 $M_{\odot}$, respectively, and aged the galaxies using a relatively current (1995) version of the spectral evolution code of Bruzual & Charlot (1993). In accordance with the GK model, we assume a SMC extinction law (Bouchet et al. 1985) and $E(B-V) = 0.1$ for all but the two reddest morphological types, and we assume that $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ throughout.

GK do not specify the surface brightness properties of their sample, so we adopt values derived from local observations and the relation between star formation history and morphological type. We take the three reddest classes of objects in GK’s model (GK classes 9–11; $B - V \approx 0.85$) to represent elliptical galaxies with a de Vaucouleurs profile with intrinsic half-life radii determined by Binggeli, Sandage, & Tarenghi (1984). For the next three reddest classes (GK class 6–8; $0.65 \leq B - V \leq 0.85$) to represent Sa–Sc galaxies with surface brightnesses given by Freeman’s law (Freeman 1970), on which we superimpose an exponential profile for the bulge with a total flux equal to 0.25 that of the disk and a scale length equal to 0.082 that of the disk (Courteau, de Jong, & Broeils 1996). We take the five bluest classes to be irregular late spiral galaxies (GK class 1–5; $B - V \leq 0.65$) with a surface brightness for the disk identical to that for the Sa–Sc galaxies. Since GK do not specify a distinct star formation history, for simplicity we assume the same star formation history for the bulges and the disks. We mimic seeing and other smearing effects by convolving the angular profiles of each simulated galactic image with a Gaussian point-spread function. We consider the disk galaxies to be oriented at an ensemble of incident angles, and we apply the selection criteria used in various determinations of the LF in a way very similar to that outlined in Yoshii (1993).

From these models, we calculated the luminosity functions that would have been determined by Loveday et al. (1992), Marzke, Huchra, & Geller (1994), Lin et al. (1996), and Mobasher, Sharples, & Ellis (1993) from the Automatic Plate Measuring (APM), Center for Astrophysics (CfA), Las Campanas, and Anglo-Australian redshift surveys, respectively. Our calculations are shown in Figure 1. Because the selection criteria for these surveys are often variable from field to field or are even somewhat unclear, we consider the selection criteria we have employed to be “average” estimates of the true selection criteria. For the APM survey, we selected galaxies with apparent magnitudes between 15 or 17.15 $B_1$ mag and whose surface brightness is at least 24.5 $B_1$ mag arcsec$^{-2}$ over a region with a 1.15 radius (Maddox et al. 1990). For the CfA survey, we selected galaxies with apparent magnitudes brighter than 15.5 $B_2$ mag and whose surface brightness is at least 23.5 $B_2$ mag arcsec$^{-2}$ over a region with a 4.5 radius—criteria we consider only to be a “reasonable” estimate. To mimic the scatter in the relationship between Zwicky magnitudes and $B_1$ mag, we convolved the derived LF with a Gaussian of standard deviation 0.35 mag (Bothun & Cornell 1990). For the Las Campanas Redshift Survey (LCRS), we used the 112 fiber selection criteria given in Lin et al. (1996) and took their magnitudes to be isophotal down to a surface brightness of 23 Gunn $r$ mag arcsec$^{-2}$. For the Anglo-Australian Redshift Survey (AARS), we selected galaxies whose apparent magnitude is less than 17.2 $B_1$ mag and whose surface brightness is at least 23.5 $B_1$ mag arcsec$^{-2}$.

Using the $\chi^2$ test and taking $\sigma$ equal to $\sigma_{obs} \left(\langle N_{obs}/N_{mod}\rangle\right)^{1/2}$, we compared the LFs predicted for various interpretations of the GK model to the actual determinations. Formally, the calculated LF for the GK model (to within 0.3 mag of an observation) and our models are inconsistent with the LF of Mobasher et al. (1993), Lin et al. (1996), Loveday et al. (1992), and Marzke et al. (1994), to 8, 31, 4, and 5 $\sigma$, respectively. Since these discrepancies are arguably a result of uncertainties in both the calibrations of the observed apparent magnitudes and the normalization due to the limited volumes surveyed, we will base our comparisons on those normalizations (only for CfA and AARS) and calibrations which produced the best fits to the calculated LFs. For these best-fit parameters, the LFs of our models are still generally inconsistent with the measured LF (the LF from the LCRS is inconsistent to 19 $\sigma$), a result essentially due to the fact that the knees of the LFs are extremely well defined. For the faint ($M_r > -19.4$) end of the LF, however, we find that only the LF from the LCRS is still inconsistent. Our cycling models are especially inconsistent (model A is inconsistent to 6 $\sigma$), as they predict many more faint galaxies than are observed (Table 1).

We show the redshift distributions we predict for the Canada-France-Hawaii Redshift Survey (CFHRS; Lilly et al. 1995) for both the GK model and our models in Figure 2. In accordance with the selection procedure, we took the seeing FWHM to be 0.9 and have included those galaxies which had a central surface brightness of 24.02 $f$ mag arcsec$^{-2}$. We took their magnitudes to be isophotal down to a surface brightness of 27.52 $I$ mag arcsec$^{-2}$. The predicted overabundance at low redshifts has two sources: the very steep upturn at the faint end of the GK LF—a feature inherent in the GK model—and the additional populations of fading or cycling galaxies which are not forming stars. Since this first source of low-redshift galaxies predominates at $z < 0.05$ while the second is more uniformly spread over low redshifts, we have decided to examine the relative number of galaxies observed and predicted for the redshift bins ($0 < z < 0.05$) and ($0.05 < z < 0.15$) separately. For

$^1$ Note that the observational mean is only an estimate of the true variance, which is determined by the model.
the sake of comparison, we assume that the observed redshift distribution, though mildly incomplete, is representative.

The GK model predicts too many galaxies in the lowest redshift bin (3.5σ) but roughly the right number in the other low-redshift bin. In contrast, all our models predict too many galaxies in this other low-redshift bin (2.1–3.8σ inconsistency). We have summarized these results in Table 1 along with the relative consistency levels of these models to the faint end of the LCRS r-band LF. In Table 1 we have also included the cumulative degree to which the CFHRS and the faint end of the LCRS r-band LF rule out the various models considered in this Letter. Of course, one should interpret these results with some caution, as our analysis makes the questionable assumption that the galaxies in the CFHRS are unclustered.

Ignoring surface brightness selection effects, we have calculated number counts in the B_J and K bands for the GK model and our models. We display these calculations in Figure 3 along with a comparison to a set of recent observations.2 The GK model and our interpretations of it agree reasonably well with the observations in the B_J band, though the predictions seem to be about 25% too low and too high on a portion of the bright and faint ends in the K band, respectively. Although some of this difference can be attributed to the use of different versions of the Bruzual & Charlot (1993) spectral evolution code, much of this difference simply results from the mildly imperfect fit to the number counts used in producing the GK model.

To determine the sensitivity of the present results to the surface brightness properties of these nonphysical blue galaxies, we repeated our calculations, assuming a surface brightness lower than Freeman’s law by 1.5 mag arcsec^2. In accord with expectations, we calculated that fewer fading

\[a\] Percent excess of predicted galaxies over those observed at the faint end (\(M_r \leq -19.4\)) of the LCRS (Lin et al. 1996).

\[b\] Cumulative inconsistency of the model predictions with the three observables in this table.

\[2\] Note that for the purposes of this figure, the error bars on the number counts from Metcalfe et al. (1991) and Metcalfe et al. (1995) are equal to the sum in quadrature of half the estimated completeness correction and the Poissonian error times 1.5.

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**TABLE 1**

| Model | LCRS Faint Galaxy Excess* | CFHRS Number Predicted (0 < z < 0.05) (3 observed) | CFHRS Number Predicted (0.05 < z < 0.15) (22 observed) | Cumulative Inconsistency Levelb |
|-------|--------------------------|---------------------------------|---------------------------------|-------------------------------|
| GK    | 6% (1.4σ)                | 17 (3.5σ)                       | 24 (0.4σ)                       | 3.3σ                          |
| A     | 68% (5.3σ)               | 20 (3.8σ)                       | 35 (2.1σ)                       | 6.5σ                          |
| B     | 43% (3.2σ)               | 19 (3.6σ)                       | 41 (2.9σ)                       | 5.2σ                          |
| C     | 0% (0.9σ)                | 19 (3.7σ)                       | 46 (3.5σ)                       | 4.8σ                          |
| D     | 11% (1.3σ)               | 21 (3.9σ)                       | 48 (3.8σ)                       | 5.2σ                          |

* Percent excess of predicted galaxies over those observed at the faint end (\(M_r \leq -19.4\)) of the LCRS (Lin et al. 1996).

* Cumulative inconsistency of the model predictions with the three observables in this table.

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FIG. 2.—Predicted CFH redshift distribution based on the GK model (thick solid line) and our models: model A (rapid cycling), dotted line; model B (cycling), short-dashed line; model C (slow cycling), long-dashed line; model D (pure fading), thin solid line; with a comparison to CFHRS (Lilly et al. 1995) (histogram). See text for more detail on models.

FIG. 3.—Number counts in the B_J and K bands based on the GK model (thick solid line) and our models: model A (rapid cycling), dotted line; model B (cycling), short-dashed line; model C (slow cycling), long-dashed line; model D (pure fading), thin solid line; with a comparison to the observations of Metcalfe et al. (1991), Metcalfe et al. (1995), Moustakas et al. (1995), Djorgovski et al. (1995), and Gardner et al. (1993) displayed as filled circles, filled squares, asterisks, open squares, and open triangles, respectively. See text for more detail on models.
galaxies and fewer cycling galaxies would be observed in both the LFs considered and the CFHRS. For these lower surface brightness galaxies, we find that both the GK model and our models can be made consistent with the faint end of the LFs considered. Nevertheless, the GK model and our models are still inconsistent with the number of galaxies at low redshift to 3.2 \( \sigma \) and 4.1 \( \sigma \), respectively. Therefore, while lowering the surface brightness of the nonphysical blue galaxies in the GK model permits a reconciliation with the faint end of the LCRS LF, it does not permit a reconciliation with the lack of low-redshift galaxies in the CFHRS. Of course, one could always suppose that the nonphysical blue galaxies have even lower surface brightnesses than we have considered, i.e., greater than 23.1 \( B_j \) mag arcsec\(^{-2}\), but at some point, this lower surface brightness would remove these galaxies from other observations as well, such as the color distributions these nonphysical blue galaxies were originally employed to explain. In fact, the observed properties of the galaxies responsible for the dark counts excess only require a steepening of the low-luminosity end of the LF in the distant universe, \( z \gtrsim 0.5 \) (Treyer & Silk 1994). Fading by expansion, due perhaps to a very substantial wind that drives mass loss, might be invoked to reconcile the high-redshift data with the local observations, but we have not explored this possibility (see Babul & Rees 1992).

3. CONCLUSIONS

In this Letter we have proposed various physical interpretations of the nonphysical population of blue galaxies in the GK model and have calculated how these interpretations would be manifested in various determinations of the redshift distribution, the luminosity function, and the number counts. First, we find that the GK model and all our models predict too many galaxies at low redshift (0 < \( z < 0.05 \)) in the CFHRS—a result which is intrinsic to the GK model itself. Glazebrook et al. (1995) previously reported this low redshift excess with regard to a similar model (Koo, Gronwall, & Bruzual 1993). For our models, we predict an additional low-redshift population that exceeds the observed galaxies in CFHRS in the redshift range 0.05 < \( z < 0.15 \). Second, for our cycling models, we predict that too many intrinsically faint galaxies would be observed in the LCRS LF. If one supposes this bluest class of galaxies has lower surface brightnesses, i.e., 23.1 \( B_j \) mag arcsec\(^{-2}\), we no longer find an excess of galaxies at the faint end of the LCRS LF. Nevertheless, there is still a discrepancy between the number of galaxies observed in the lowest redshift bins (0 < \( z < 0.15 \)) and the number predicted from the GK model and our models, respectively. Hence, passive evolution using "normal" galaxies, essentially in the spirit of the GK model and the modifications that we have advocated, fails to account both for the deep counts and for the low-redshift counterparts of the distant galaxies. One needs to add either luminosity evolution, in the form, for example, of dynamical fading or a top-heavy IMF, or number evolution, as occurs in merging histories, or some combination of these effects.

Recently, in a model which is somewhat similar to the GK model, Pozzetti et al. (1996) have presented an alternative set of models which propose to explain much of the current observational data (number counts, redshift distributions, and color distributions) with essentially passive evolution. One of the most notable improvements of this new model over the GK model is the relative absence of galaxies at low redshifts (\( z < 0.05 \)). Despite this improvement, this new model invokes a population of eternally young (0.1 Gyr) galaxies quite similar to those galaxies used in the GK model. Making these galaxies physical in the ways outlined here would have similar observational effects to those we have calculated, though our own calculations have shown that the corresponding low-redshift effects are not large enough to cause a problem with the observations employed in this paper. The basic reason for this difference is that the nonphysical blue galaxies in this model make up a much smaller fraction of the galaxies seen at any apparent magnitude than the nonphysical blue galaxies do in the GK model. Nevertheless, for the case that galaxies have "normal" surface brightnesses, this model still predicts a 200% excess in the number of galaxies found at the faint (\( M_B \approx -18.6 \)) end of LF derived from the LCRS.

As a final note, while we have examined how both the GK model and our physical interpretations would manifest themselves in various determinations of the redshift distribution, number counts, and luminosity function at zero redshift, we suspect that it may also be fruitful to consider other constraints on passive evolution models from various recent studies that have shown, albeit with sparser data, that the luminosity function steepens (Ellis et al. 1996) or brightens (Lilly et al. 1995) as one progresses back in redshift space.

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