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 (1995), 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 which fade
after they reach the age specified in the Gronwall and 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_J 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 CFH redshift survey (Lilly
et al. 1995) and at the faint end of the Las Campanas luminosity function (Lin
et al. 1996). 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, hereinafter 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 eleven morphological classes, GK allow the luminosities and colors of the galaxies to evolve in a way that is consistent with their construction of their morphological classes. GK require that the remaining three classes be very blue and completely non-evolving. 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 1995). In this paper, we impose the aforementioned physical interpretations on the non-physical 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 non-physical blue galaxies from $z = 0$ to $z = 1$. We believe that $z = 1$ is early enough to account for a predominance of blue galaxies seen at faint magnitudes–which the GK model attempts to explain with a population of non-physical 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 non-physical blue galaxies with periods of no star formation. If the B-V colors specified for the non-physical blue galaxies in the GK model are not to be more than 0.10 magnitude 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 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) IMF with upper and lower mass limits of $0.1 M_\odot$ 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, and 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; $B - V \geq 0.85$) to represent elliptical galaxies with a de Vaucouleurs profile with intrinsic half-life radii determined by Bingelli, Sandage, & Tarenghi (1984). We take 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 one quarter 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, 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 et al. (1993) from the APM, 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 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 and 17.15 B_J mag and whose surface brightness is at least 24.5 B_J mag/arcsec^2 over a region with a 1.15 arcsec radius (Maddox et al. 1990). For the CfA survey, we selected galaxies with apparent magnitudes brighter than 15.5 B_J mag and whose surface brightness is at least 23.5 B_J mag/arcsec^2 over a region with a 4.5 arcsec radius– criteria we consider only to be a "reasonable" estimate. To mimic the scatter in the relationship between Zwicky magnitudes and B_J 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_J mag and whose surface brightness is at least 23.5 B_J mag/arcsec^2.

Using the χ^2 test and taking σ equal to $\sigma_{obs}(\sqrt{N_{model}/N_{obs}})$, [1] 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 magnitude 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 σ, 31 σ, 4 σ, and 5 σ, 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 σ), 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 σ) 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 (Lilly et al. 1995: CFHRS) 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 arcsec and have included those galaxies which had a central surface brightness of 24.02 I 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

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[1]Note that the observational mean is only an estimate of the true variance, which is determined by the model.

very steep upturn at the faint end of the GK LF–a feature inherent to 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 the sake of comparison, we assume the observed redshift distribution, though mildly incomplete, is representative.

The GK model predicts too many galaxies in the lowest redshift bin $(3.5\,\sigma)$ 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 $(2.1\text{-}3.8\,\sigma$ 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 high and low on a portion of the bright and faint ends in the K band, respectively. Though some of this difference can be attributed to the use of different versions of the Bruzual & Charlot 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 non-physical blue galaxies, we repeated our calculations, assuming a surface brightness lower than Freeman's law by 1.5 mag/arcsec^2. In accordance with expectations, we calculated that fewer fading 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

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[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 one and a half.

with the number of galaxies at low redshift to 3.2 σ and 4.1 σ, respectively. Therefore, while lowering the surface brightness of the non-physical blue galaxies in the GK model permits a reconciliation with the faint end of the Las Campanas LF, it does not permit a reconciliation with the lack of low redshift galaxies in the CFHRS. Of course, one could always suppose these non-physical 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 non-physical blue galaxies were originally employed to explain. In fact, the observed properties of the galaxies responsible for the deep 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 (cf Babul & Rees 1992).

3. Conclusions

In this Letter, we have proposed various physical interpretations of the non-physical 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. Firstly, we find that the GK model and all our models predict too many galaxies at low redshift ($0 < z < 0.05$) in the CFHRS–an excess 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 which exceeds the observed galaxies in CFHRS in the redshift range ($0.05 < z < 0.15$). Secondly, 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, Bruzual, & Zamorani (1996) have presented an alternate 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 non-physical blue galaxies in this model make up a much smaller fraction of the galaxies seen at any apparent magnitude than the non-physical 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 ($M_r \approx -18.6$) 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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Fig. 1.— Luminosity functions calculated for the GK model and our models (thick solid = GK model, dotted = Model A (rapid cycling), short dashed = Model B (cycling), dashed = Model C (slow cycling), thin solid = Model D (pure fading)). For comparison, the LFs of Loveday et al. (1992), Marzke et al. (1994), Mobasher et al. (1993), and Lin et al. (1996) are all plotted on this figure using circles, triangles, diamonds, and squares, respectively. See text for more details on models.

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

Fig. 3.— Number counts in the B_J and K bands based on the GK model and our models (thick solid = GK model, dotted = Model A (rapid cycling), short dashed = Model B (cycling), dashed = Model C (slow cycling), thin solid = Model D (pure fading)) 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 solid circles, solid squares, asterisks, hollow squares, and hollow triangles, respectively. See text for more detail on models.

Table 1.   The inconsistency level of the present models with respect to various observations.

Model	LCRS Faint Gal. Excess[a]	CFHRS # predicted $0 < z < 0.05$ 3 observed	CFHRS # predicted $0.05 < z < 0.15$ 22 observed	Cumulative Inconsistency Level[b]
GK	6% (1.4 σ)	17 (3.5 σ)	24 (0.4 σ)	3.3 σ
A	68% (5.3 σ)	20 (3.8 σ)	35 (2.1 σ)	6.5 σ
B	43% (3.2 σ)	19 (3.6 σ)	41 (2.9 σ)	5.2 σ
C	0% (0.9 σ)	19 (3.7 σ)	46 (3.5 σ)	4.8 σ
D	11% (1.3 σ)	21 (3.9 σ)	48 (3.8 σ)	5.2 σ

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

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

Number Density (Mpc^{-3}/mag)

$M_K - 4$, $M_r - 4$, M_{B_J}

Mobasher et al. 1993
Lin et al. 1996
Loveday et al. 1992
Marzke et al. 1994