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# BINARY MERGING: THE OTHER MODE OF GALAXY EVOLUTION

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## ABSTRACT

We discuss the mode of galaxy evolution based on merging after binary encounters, complementary to the mode based on direct hierarchical collapses. We show that the merging-driven mode produces, mainly by dynamical evolution, a local Schechter-like luminosity function starting at $z \sim 2$ from a steep mass distribution like Press & Schechter's. Such evolution inside galaxy systems provides a quantitative estimate of the Butcher-Oemler effect and yields an excess of faint blue galaxy counts like that observed.

*Subject headings:* cosmology: theory — galaxies: evolution — galaxies: formation

## 1. INTRODUCTION

Galaxy luminosity functions fitting both the local data and those at higher $z$ are not easily accounted for in terms of direct hierarchical collapse (DHC) of initial density perturbations.

DHC predicts a distribution $N(M, z)$ of galactic masses with a shape always close to that first derived by Press & Schechter (1974, hereafter P&S): a soft cutoff at the large-$M$ end; and a steep power law at the small-$M$ end, namely, $N(M)\, dM \propto M^{-\Gamma}\, dM$ with $\Gamma \approx 2$ (see, e.g., Lacey & Silk 1991; Blanchard, Valls-Gabaud, & Mamon 1992). Star formation may cause $M/L$ to vary as to differentiate the luminosity function $N(L)$ from $N(M)$; at the faint end, feedback from stellar energy release is expected to suppress further star formation in small galaxies, producing $L \propto M^p$ with $p > 1$. But a smooth formation efficiency flattens the slope of $N(L) \propto L^{-\alpha}$ only to $\alpha \gtrsim 1.35$ (White & Frenk 1991). Further flattening requires short starbursts triggered by interactions in groups (Lacey & Silk 1991).

The local $N(L)$ (Efstathiou, Ellis, & Peterson 1988; Binggeli, Sandage, & Tammann 1988) generally lies in between the above two results, with some variance. Earlier $N(L, z)$ are probed by the counts of faint galaxies in the $B$ band, and these show a large excess over the uniform distribution, with a smaller one in the $K$ band (Cowie, Songaila, & Hu 1991; Broadhurst, Ellis, & Glazebrook 1992; and legend to Fig. 2). As discussed by several authors (Broadhurst, Ellis, & Shanks 1988; Lacey & Silk 1991; Weinberg et al. 1991), $N(L, z)$ always flattened by starbursts would underproduce the faint $B$ counts. An independent population of numerous small galaxies bursting at $z \lesssim 1$ requires some tuning and a smooth connection with the local counterparts. The counts would be accounted for by $N(L, z)$ steepening with $z$, and with the appropriate number and luminosity evolution.

The solutions to these problems are constrained by the modest $\langle z \rangle \approx 0.3$–$0.4$ indicated by growing spectroscopic samples out to $B \approx 24$ (Colless et al. 1990; Cowie et al. 1991). Simple luminosity evolution implies considerably larger $\langle z \rangle$; in addition, it would require FRW volumes stretched with $\Omega_0 \ll 1$ (Rocca-Volmerange & Guiderdoni 1990), a condition adverse to any evolution at modest $z$.

The problems with the DHC mode are intrinsic. The gravitational instability causes sequential collapses of initial overdensities with power spectrum $\langle |\delta_k|^2 \rangle \propto k^\nu$ ($\nu \approx -2$), and the resulting $N(M, z) \propto f(M/M_c)/M_c^2(z)$ is self-similar. It retains the slope $\Gamma = 1.5 - \nu/6 \approx 2$ at all $z$'s; the typical mass shifts as $M_c(z) \propto (1 + z)^{-6/(\nu+3)}$ in a critical universe; the associated time scale is $\tau_c = 3t/2$.

Many of the above authors suggest that such problems might be alleviated, if not solved, by a generous dose of merging events. These are unlikely to be of the kind already included in the DHC dynamics, that may be referred to as coalescence of perturbations correlated in the initial conditions. In fact, at $z < 1$ such coalescence builds up mainly masses typical of groups or clusters with only transitory, large substructures of modest contrasts. The galaxies that persist with their high contrasts and small visible radii must have frozen out of the hierarchy, likely by dissipation in the baryonic component (see Carlberg & Couchman 1989).

The question arises concerning the fate of galaxies as distinct units within larger structures like groups and clusters, whose relaxation at formation further erases correlations. Here we shall explore the evolution at the faint end caused by random inelastic galaxy collisions, possibly enhanced by mutual attraction.

## 2. A SOLUTION FOR THE LOCAL MASS DISTRIBUTION

Collisions followed by merging introduce the new time scale $\tau \sim 1/n\Sigma V$. Here the number density $n \sim \rho_a/M$ and the average relative velocity $V$ are both provided by the environments that surround the galaxies and constitute higher hierarchical structures in a DHC scenario. The galaxies themselves, with their radii $r$ and internal dispersions $v \sim (GM/r)^{1/2}$, contribute the cross section $\Sigma = \pi(r_1 + r_2)^2[1 + 2G(M_1 + M_2)/(r_1 + r_2)V^2]$ for $v \sim V$ (see Saslaw 1985). The first term represents geometric collisions (GCs), and the second describes gravitationally focused interactions (FIs). Both components scale as $M^\lambda$, with $\lambda = 2/3$ or $4/3$, respectively; correspondingly, $\tau \propto M^{1/3}$ or $\tau \propto M^{-1/3}$ holds.

The growth by binary merging of the characteristic mass $M_*(t)$ is driven on the scale $\tau$ after $\dot{M}_*(t) \propto M_*/\tau$. The $M$-dependence of $\tau$ also selects the *kind* of evolution undergone by $N(M, t)$; see Cavaliere, Colafrancesco, & Menci (1991, 1992; hereafter together CCM). Here we focus on the kind which works primarily at the *faint* end when GCs with their scale $\tau \propto M^{1/3}$ are dominant; this occurs when $V^2 \gtrsim 3v^2$ as is the case in large groups or in clusters.

The statistics of binary merging comprises creation and destruction events with rate $\tau^{-1}$, combined in an "aggregation equation" of the form $\partial N/\partial t = NN\Sigma V - NN\Sigma V$. This has been considered by Silk & White (1978) and by Silk (1978); it has been recently discussed and recomputed by CCM to which we refer for technical details.

The equation is of integrodifferential form, so all its solutions begin with a *transient* stage during which memory of the initial conditions is erased. This *asymptotes* to a self-similar regime (stable when GCs dominate), where $N(M, t) = \psi(m)/M_*^2(t)$ holds with $m \equiv M/M_*$. Then the shape is given by

$$(m \ll 1) \quad m^{-\xi} \leftarrow \psi(m) \rightarrow m^{-\lambda}e^{-m} \quad (m \gg 1)\ . \tag{2.1}$$

The exponent $\xi$ takes on values related to $\langle m^\lambda \rangle$, the $\lambda$th moment of $\psi(m)$, by:

$$\xi = 2 - \langle m^\lambda \rangle \sim 1.2\text{–}1.3\ . \tag{2.2}$$

The range in $\xi$ is obtained numerically by CCM. The value 1.2 applies to the limit of pure GCs ($\lambda \rightarrow 2/3$); an appreciable FI component ($\lambda = 4/3$) as obtains for $3v^2(M_*)/V^2 \sim 1$, tilts $\xi$ toward values closer to 1.3. The shape in equation (2.1) is achieved over times of order $t_d$, the dynamical scale of the host structure, before any phase transition (see CCM) can occur. Such shape is independent of details of the initial one, as long as this describes an excess of small galaxies.

The luminosity function obtains from $L \propto M^p$. At the faint end, where low surface brightness galaxies are observed, one expects $p > 1$. The consistent value of $p$ may be estimated from $L \propto v^2\dot{M}$ (cf. White & Frenk 1991), using the specific relations $v^2 \propto M/r \propto M^{2/3}\rho^{1/3}$ ($\rho$ being the galaxy internal density) and $\dot{M} \propto M/\tau$. Star formation is likely driven by the same galaxy interactions (see Lacy & Silk 1991; Broadhurst et al. 1992) out to somewhat larger impact parameters with a rate $s \gtrsim \tau^{-1}$. Then with GCs dominant to imply $\tau \propto M^{1/3}$, and with $\rho(M)$ only weakly increasing, the scaling $L \rightarrow M^{4/3}$ obtains.

To sum up, $N(L)$ is quite flatter than the initial $N(M)$, and approaches both at the *faint* and at the *bright* end a shape strongly reminiscent of the Schechter representation of the local data. The argument applies in its neatest form to the type-specific $N(L)$ for dwarfs (Binggeli et al. 1988), of most interest here.

## 3. EVOLUTION IN HIERARCHICAL STRUCTURES

We now discuss in closer detail the *transient* stage. We focus on galaxies with masses $M$ interacting in a system with total mass $\mathcal{M}$, overall radius $R$, and velocity dispersion $V$; the latter quantities depend on $z$ according to the DHC scenario. The merging time in a critical universe scales with $z$ and with $\mathcal{M}$, $R$, $V$, as

$$\tau \propto t_d(M/\mathcal{M})^{1/3}(1 + z)^{-(17+7\nu)/2(\nu+3)}\ , \tag{3.1}$$

where $t_d \sim R/V$ at given $z$, and the index $\nu > -2$ refers to the host structures.

The latter, after the DHC scenario, are reshuffled into larger and larger systems after a finite survival time averaging to $\tau_c$ (Cavaliere, Colafrancesco & Scaramella 1991). Accordingly, we divide the range from $z_u \approx 2$ into bins, each starting at the $z_i$ corresponding to the dynamical time $t_{di} \sim \tau_{ci}$ of a hierarchical step. We follow the evolution of $N(M, z)$ with numerical solutions of the aggregation equation for each step, starting the first one with a P&S initial condition. Each following step starts with the initial condition provided by the outcome of the previous one and is marked by a larger $V$ which enhances the relative importance of GCs over FIs. The full history of $N(M, z)$ is shown in Figure 1.

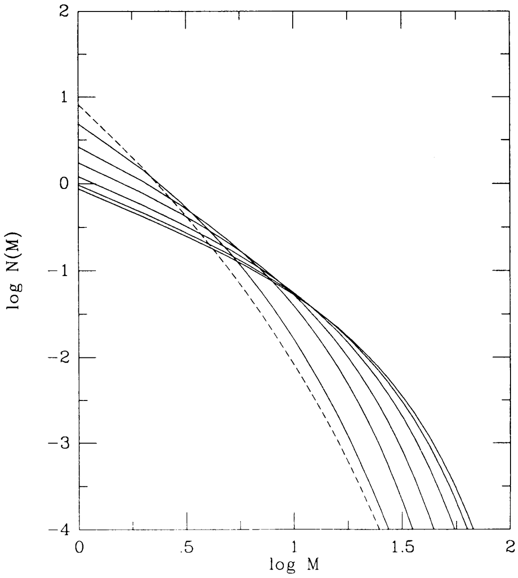


FIG. 1.—Evolution of the mass distribution $N(M, z)$ under pure GCs with $\Sigma \propto M^{2/3}$ Arbitrary units are used on both axes. The distributions shown correspond to the redshifts $z = 0$, 0.2, 0.45, 0.75, and 1.1. The last, dashed line shows the P&S initial shape at $z = 2.2$. Note that the number evolution is much faster than the change of the characteristic mass.

To illustrate the efficiencies, we give in Table 1 the probability of merging $\mathcal{P}(z_i)$, defined as the frequency of host systems in the $i$th step having $\tau < \tau_c$. This condition requires a large galaxy density, hence large system masses $\mathcal{M}$; using the expressions of $\tau$ and $\tau_c$, we obtain a lower limit $\mathcal{M}_m$ of the form

$$\mathcal{M} > \mathcal{M}_m(M, z_i) \propto M\left(\frac{1 + z_i}{1 + z_u}\right)^{-6(2+\nu)/(\nu+3)}\ . \tag{3.2}$$

The probability $\mathcal{P}$ is found by integrating the mass distributions for the galaxies and for the host systems from their respective lower limits

$$\mathcal{P}(z_i) = \frac{\int_{M_l}^{\infty} dM\, N(M) \int_{\mathcal{M}_m}^{\infty} d\mathcal{M}\, N(\mathcal{M})}{\int_{M_l}^{\infty} dM\, N(M) \int_{\mathcal{M}_l}^{\infty} d\mathcal{M}\, N(\mathcal{M})}\ . \tag{3.3}$$

The results collected in Table 1 show that the efficiency increases rapidly with increasing redshift, from local values $\sim 5\%$. Thus, while part of the flattening of $N(M, z)$ from the initial shape takes place for $z \gtrsim 1$, yet important evolution is observable at $z \lesssim 0.5$; see Figure 1. The associated $M_*(z)$ averaged over the hierarchical steps is closely approximated by $(1 + z)^{-\eta}$ with $\eta \approx 1.2$.

TABLE 1

MERGING PROBABILITIES IN REDSHIFT INTERVALS CORRESPONDING, IN A CRITICAL UNIVERSE, TO LIFETIMES OF TYPICAL HOST STRUCTURES[a]

| | $\Delta z$ | | | | | |
|---|---|---|---|---|---|---|
| | 0–0.2 | 0.2–0.45 | 0.45–0.75 | 0.75–1.1 | 1.1–1.5 | 1.5–2.2 |
| $P(z)$.......... | 0.05 | 0.11 | 0.19 | 0.28 | 0.40 | 0.60 |

[a] See § 3.

## 4. IMPLICATIONS

Here we give a preliminary discussion of two observable implications of the interaction-driven evolution shown in Figure 1.

One indicator of interactions may be provided by the so-called Butcher-Oemler effect (see Butcher & Oemler 1984), that is, the enhanced fraction $f$ of blue or starburst galaxies observed in some 15 rich clusters with $z \gtrsim 0.3$, albeit with large cluster-to-cluster variations. The picture is confirmed by closer looks at $z \approx 0.4$ clusters with *HST* (A. Dressler, private communication). The effect has been quantified by Bower (1991) from a compilation of existing data out to $z \approx 0.5$, in the form of the gradient $\Delta f/f_0 \Delta z \approx 10$–30, where $f_0 \approx 0.03$.

A value for the gradient may be predicted from our picture of evolution under merging, on the assumption that stellar bursting is directly related to galaxy interactions as in § 3. Then inspection of Table 1 leads to an expectation value $\Delta f/f_0 \Delta z \approx 12$. A considerable variance is also expected around this value due to individual spreads of the dynamical quantities in equation (3.1), including the variance in the (small) number of groups that coalesce into a cluster in the DHC picture.

As another, integral test we report a pilot calculation of the expected $B$-counts, under the assumption that the galaxies involved spent a major fraction of their lifetime inside a structure belonging to the hierarchy. Our dynamics predicts $N(M, z)$ to steepen cumulatively with increasing $z$, a form of strong density evolution phenomenologically considered by Broadhurst et al. (1988).

To convert $N(M, z)$ into counts, we use again $L \propto M^{4/3}$ (see § 2). This is to be combined with the luminosity evolution expected from the enhanced rate of star formation in galaxy interactions. Enhanced star formation in faint blue galaxies is indicated, e.g., by the increased equivalent widths of the [O II] line at 3727 Å (Broadhurst, Ellis, & Glazebrook 1992). The rate is again taken $s(z) \gtrsim \tau^{-1}(z)$, and is provided by equation (3.1) *averaged* over the hierarchical steps. Thus the characteristic luminosity reads $L_*(z) \propto M_*^{4/3}(z)s(z)$, where $s(z) \sim \tau^{-1} \propto (1+z)^{\mu}$ with $\mu \approx 1.5$.

Then $N(L, z)$ is convolved (see Weinberg 1972) with the cosmological volumes and the appropriate $k$-corrections to yield the number counts per unit blue magnitude $m_B$. We integrate up to $z_u = 2.2$ and adopt a characteristic luminosity locally corresponding to $M_{B*} = -20.5$. Because the relevant evolution concerns mainly the faint end, an evolving type-specific $N(L, z)$ with a fainter $M_{B*}$ does not change the results provided we add a complementary, nearly invariant component. In this pilot calculation, we adopt for the blue spectral region a neutral $k$-correction (see Lilly, Cowie, & Gardner 1991; Koo & Kron 1992).

The predicted number counts are plotted in Figure 2 together with data from various authors. In Figure 3 we plot the corresponding $z$-distributions in the range $20 < m_B < 22.5$ to show accord with the present data as for $\langle z \rangle$ and for the high-$z$ decline. The distribution in the range $22.5 < m_B < 25$ shows the trend toward larger $\langle z \rangle$ for fainter galaxies. The counts in the $K$-band will be lower at the faint end for two reasons: first, the $k$-correction acts on a spectrum initially flat in wavelength (see, e.g., Koo & Kron 1992); second, the longer lifetime of the stars contributing to this band weakens the effective dependence $s(z)$ in $L_*(z)$.

## 5. DISCUSSION

We have computed the galaxy evolution driven by binary merging. Our key result is that the mass distribution during the transient stage is *not* self-similar; instead, the faint end slope *increases* rapidly into the past (see § 3). The local rates, of order 5% for masses close to $M_*$ (Toomre 1977; Schweizer 1992), are enhanced with increasing $z$ (faster than $1 + z$ on average) *and* with decreasing mass ($\propto M^{-1/3}$), as given by equation (3.1) and by the values in Table 1.

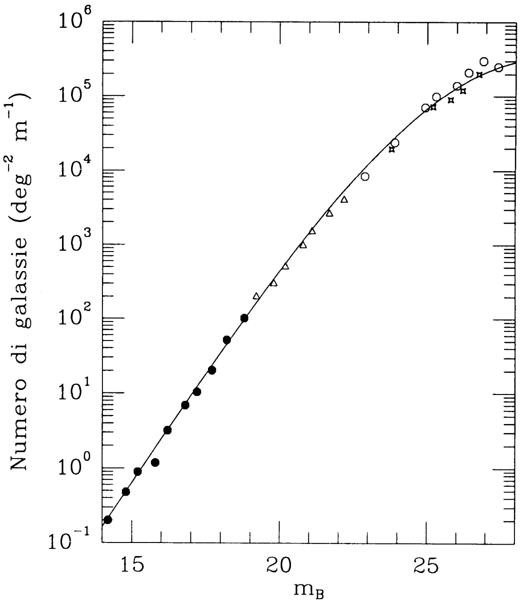


FIG. 2.—Our computed blue galaxy counts (*solid line*), compared with data from several authors: Collins & Nichol (1992) (*filled circles*); Jones et al. (1991) (*open triangles*); Tyson (1988) (*open circles*); Lilly, Cowie, & Gardner (1991) (*stars*).

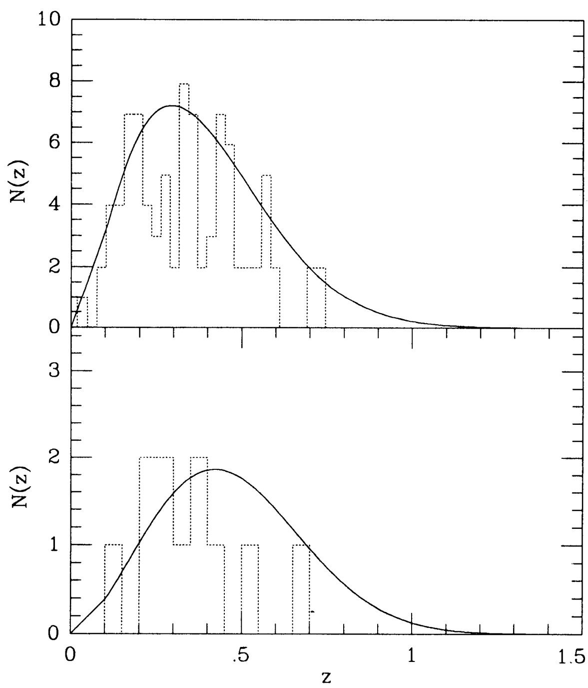


FIG. 3.—Top panel shows the redshift distribution of galaxies in the range $20 < m_B < 22.5$ (*solid line*), with the histogram showing the data from Colless et al. (1990). Bottom panel shows the distribution in the range $22.5 < m_B < 24$ (*solid line*), compared with the data from Cowie et al. (1991); the normalization is obtained scaling the counts in Fig. 2 with the area ratio of the two data samples.

The flattening is cumulative along the cosmic time starting from a *generic*, steep initial condition; its *asymptotic* value yields a Schechter-like luminosity function starting from a P&S mass distribution, mainly by dynamical evolution (see § 2). The slope flattens with a strong depletion of small galaxies, but with little increase of the characteristic $M_*$, from $\alpha \approx 2$ down to $\approx 1.2$; the actual value depends on the specific history of *individual* condensations. The change of the characteristic $L_*(z) \propto M_*(z)^{4/3} s(z)$ is even slower, because the increased star formation rate $s(z) \propto (1+z)^{1.5}$ counteracts the factor $(1+z)^{-4/3}$ contributed by the decrease of $M_*(z)$. The resulting luminosity function scales as $\phi_* M_*^{-1} L_*^{\alpha-1}$, with $\phi_*(z)$ increasing only weakly with $z$ to conserve mass as the slope $\alpha(z)$ steepens; cf. the phenomenological treatment by Guiderdoni & Rocca-Volmerange (1991). At low $z$ when $\alpha \approx 1.2$ holds, density evolution dominates; only for $z \gtrsim 1$, when $\alpha$ increases substantially, the luminosity component can matter.

The process in the making will be observed in clusters at intermediate $z$ as an average excess of blue or poststarburst galaxies. Looking farther out, it yields an excess of faint blue counts at $z \gtrsim 0.3$ (see § 4), *provided* that the majority of small galaxies reside for a considerable fraction of their lifetime within hierarchical structures like groups and clusters, or within lower dimensionality condensations like filaments and sheets (cf. Broadhurst et al. 1990).

The overall picture is as follows. Binary merging constitutes a *second mode* of galaxy evolution *complementary* to the canonical DHCs. In persistent structures (with lifetime $\gtrsim 3t/2$), the initial mass distribution provided by DHCs is remolded by binary mergings at the bright and at the faint end, as described by the aggregation equation (CCM). The *faint* end of the $N(L, z)$ will continue its evolution in groups and clusters (or in filaments and sheets), incorporating a declining formation of small galaxies. Similar evolutions hold for other cross sections of the form $\Sigma \propto M^\lambda$ with $\lambda < 1$; smaller values lead to flatter luminosity functions. The intermediate-mass range, where spirals are mainly located, is least affected as there the merging rate is high but dominated by large-small interactions.

The merging-driven evolution differs from that envisaged by the pure DHC picture also as to the space correlations. In fact, it works on initially small galaxies, conceivably weakly correlated; at reshufflings of the host structures, the correlations are partly reset to catch with the pattern governed by nonlinear clustering (Melott 1992; Couch, Jercevich, & Boyle 1992); during the structure survival, merging contributes only flat correlations (Cavaliere & Menci 1993).

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