EARLY HIERARCHICAL FORMATION OF MASSIVE GALAXIES TRIGGERED BY INTERACTIONS

N. MENCI, 1 A. CATALIAPER, 2 A. FONTANA, 1 E. GIALLONGO, 1 F. POLI, 1 AND V. VITTORINI 1

Abstract

To address the problem concerning the early formation of stars in massive galaxies, we present the results of a semianalytic model of galaxy formation that includes a physical description of starbursts triggered by galaxy interactions. These originate from the destabilization of cold galactic gas that occurs in galaxy encounters, which in part feeds the accretion onto black holes that powers quasars and in part drives circumnuclear starbursts at redshifts $z \approx 2-4$, preferentially in massive objects. This speeds up the formation of stars in massive galaxies at high redshifts without altering it in low-mass galactic halos. Thus, at intermediate $z$, $\approx 1.5-2$, we find that a considerable fraction of the stellar content of massive galaxies is already in place, at variance with the predictions of previous hierarchical models. The resulting high-$z$ star formation rate and $B$-band luminosity functions and the luminosity and redshift distribution of galaxies in the $K$ band at $z \approx 2$ are all in good agreement with the existing observations concerning the bright galaxy population.

Subject headings: galaxies: formation — galaxies: high-redshift — galaxies: interactions

1. INTRODUCTION

Current hierarchical theories of galaxy formation envisage the buildup of stars in galaxies as a gradual process driven by the continuous growth of the host dark matter (DM) galactic halos through repeated merging events. These also progressively increase the gas mass in the growing galaxies; its subsequent radiative cooling is partially counteracted by heating due to the winds from supernovae originating from massive parent stars. The net result of such a “quiescent” star formation is a gradual increase of the stellar content of the galaxies. However, when the picture is quantitatively modeled through the semianalytic models (SAMs; Kauffmann, White, & Guiderdoni 1993; Somerville & Primack 1999; Cole et al. 2000; Menci et al. 2002), the resulting amount of stars formed at high $z$ in the bright galaxy population is lower than indicated by several observational results.

Among these we mention first the high cosmic density of bright galaxies, observed to be in excess of the model predictions at $z \approx 3-5$. It is true that several groups (e.g., Cole et al. 2000; Somerville, Primack, & Faber 2001; Fontana et al. 2003a) have shown that canonical SAMs (i.e., with no merging-induced starbursts) provide a total star formation history (integrated over all luminosities) consistent with observations. But when one focuses on the UV luminosity density produced by the brightest galaxies only, these SAMs underpredict the luminosity densities observed at $z \geq 4$ (Fontana et al. 1999, 2003a). This can be traced back to the fact that the detailed shape of the luminosity functions (LFs) from SAMs are appreciably steeper than those observed at these redshifts. Actually, the SAMs underpredict the number of faint galaxies and, for canonical SAMs with quiescent star formation only, they underpredict the bright ones (see Somerville et al. 2001).

Second and most important, the SAMs underpredict both the bright galaxies observed in the $K$-band luminosity functions at intermediate redshifts ($z \approx 1-2$; see Pozzetti et al. 2003) and the galaxies brighter than $K = 20$ counted at $z > 1.5$ (Cimatti et al. 2002). The emission in the $K$ band is largely contributed by old stellar populations, and so is a measure of the amount of stars already formed; thus, the above observations imply that the star content of massive galaxies already in place at $z \approx 2$ is larger than that resulting from the gradual star formation typical of hierarchical models. Indeed, independent, direct observations at $z \approx 2$ of the stellar mass density of massive galaxies (in the range $m_\star \approx 10^{10}-10^{11} M_\odot$) yield a fraction close to 0.3 of the present value, while the canonical SAMs (with or without starbursts) yield a fraction around 0.1 (see Fontana et al. 2003b). The above results concur, indicating that the physics of hierarchical galaxy formation still lacks some basic process that enhances star formation in massive galaxies.

Candidates for such an enhancement are starbursts triggered by galaxy interactions, as proposed by Somerville et al. (2001; see also Cavaliere & Menci 1993). The former authors assumed that satellite galaxies contained in the same host DM halo (i.e., in groups or clusters of galaxies) might undergo binary aggregations, which would not only affect their mass distribution but also brighten them by triggering starbursts. In such a model, only encounters leading to outright merging are considered; in addition, the fraction of galactic gas converted into stars during each burst is taken to be constant in time, with a parametrized dependence on the merger mass ratio that favors major mergers. The resulting starbursts, while improving the match with the observed UV LFs at $z = 3$ and 4, still do not provide enough high-$z$ star formation to account for the number of bright ($K > 20$) galaxies at $z > 1.5$ observed by Cimatti et al. (2002).

Thus, one main problem with the current SAMs is their failure to form enough stars at high $z$ in bright galaxies to match the observed bright end of the $K$-band LFs at intermediate $z$. Here we address this issue on the basis of a more complete description of the starbursts triggered by galaxy encounters. This is based on the physical model for the destabilization of cold galactic gas during galactic merging and flyby developed by Cavaliere & Vittorini (2000, hereafter CV00). The destabilized gas is assumed to feed in part the accretion onto a central supermassive black hole (BH), therefore powering quasarlike emission, and in part a burst of
star formation. The amount of destabilized gas, the duration of the bursts, and their rate as set by the galaxy encounters are determined by the physical properties of the galaxies and of their host halos, groups, or clusters. While CV00 adopted simplified derivations for the galactic properties in common DM halos, here such properties are self-consistently computed from the SAM presented in Menci et al. (2002).

In a previous paper (Menci et al. 2003), we have shown that the quasar (QSO) evolution resulting from such a model is in excellent agreement with a large set of observables. Here we focus on the circumnuclear starbursts originating from the fraction of cold gas destabilized in galaxy encounters that is complementary to the gas accreted to the central supermassive BH; such starbursts mainly affect the massive galaxy population.

We recall in § 2 the basic features of the SAM presented in Menci et al. (2002), while in § 3 we present our treatment of the new processes included in our present model, i.e., the flyby events and the associated destabilization of cold galactic gas. The results are presented in § 4, while § 5 is devoted to conclusions and discussion.

2. MODELING THE GALAXY EVOLUTION

To describe the galaxy evolution in the hierarchical scenario, we adopt the SAM described in detail in Menci et al. (2002); here we recall the basic points. We consider both the host DM halos containing the galaxies (i.e., groups and clusters of galaxies with mass $M$, virial radius $R$, and circular velocity $V$) and the DM clumps (with mass $m$, tidal radius $r$, and circular velocity $v$) associated with the individual member galaxies. The former grow hierarchically to larger sizes through repeated merging events (at the rate given in Lacey & Cole 1993), while the latter may coalesce either with the central galaxy in the common halo due to dynamic friction or with other satellite galaxies through binary aggregations. The timescale for the dynamic friction and the binary merging processes, and so the probability for such processes to occur in each timestep, are given by equations (2) and (4) in Menci et al. (2002).

We initially assume (at $z \approx 10$) one galaxy in each host structure, with the latter following the Press & Schechter (1974) mass distribution. The probability for the merging processes (dynamic friction and binary aggregations) to occur during the hierarchical growth of the hosting structure yields the differential distribution function $N(v, V, t)$ of galaxies with given $v$ in hosts with circular velocity $V$ at the cosmic time $t$. From $N(v, V, t)$ we derive the number $N_F(V, t)$ of galaxies in a host halo (membership) and the overall distribution of galaxy circular velocity $N(v, t)$ irrespective of the host.

The properties of the baryons (gas and stars) contained in the galactic DM clumps are computed as follows. Starting from an initial amount $m_0 \Omega_{b}/\Omega$ of gas at the virial temperature of the galactic halos, we compute the mass $m_c$ of cold baryons within the cooling radius. The disk associated with the cold baryons has a radius $r_d(v)$, rotation velocity $v_d(v)$, and dynamic time $t_d = r_d/v_d$ all computed after Mo, Mao, & White (1998). From such a cold phase, stars are allowed to form at the rate

$$\dot{m}_c = \frac{m_c}{t_{\text{dyn}}} \left( \frac{v}{200 \text{ km s}^{-1}} \right)^{-\alpha_s}.$$  (1)

Finally, a mass $\Delta m_h = \beta m_c$ is returned from the cool to the hot gas phase through the energy fed back by canonical Type II supernovae associated with $m_c$; the feedback efficiency is taken to be $\beta = (v/v_h)^{\alpha_b}$. The values adopted for the parameters $\alpha_s = -1.5$, $\alpha_b = 2$, and $v_h = 150$ km s$^{-1}$ fit both the local $B$-band galaxy LF and the Tully-Fisher relation, as illustrated by Menci et al. (2002).

At each merging event, the masses of the different baryonic phases in each galaxy are refueled by those in the merging partner. The further increments $\Delta m_r$, $\Delta m_\ast$, and $\Delta m_h$ from cooling, star formation, and feedback are recomputed on iterating the procedure described above.

Thus, for each galactic $v$, the star formation defined by equation (1) is driven by the cooling rate of the hot gas and by the rate of refueling of the cold gas, which in turn is related to the progressive growth of the total galactic mass along the merging tree. The related brightening of galaxies is a gradual process, and the associated star formation history is often referred to as quiescent star formation.

The integrated stellar emission $S_j(v, t)$ at the wavelength $\lambda$ is computed by convolving the star formation rate (SFR) with the spectral energy distribution $\phi_z$ obtained from population synthesis models:

$$S_j(v, t) = \int_0^t dt' \phi_z(t - t') \dot{m}_c(v, t').$$  (2)

In the following we adopt $\phi_z$ from Bruzual A. & Charlot (1993) with a Salpeter initial mass function (IMF). The dust extinction is computed as described in Menci et al. (2002). All computations are made in a $\Lambda$CDM cosmology with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, a baryon fraction $\Omega_b = 0.03$, and a Hubble constant $h = 0.7$ in units of 100 km s$^{-1}$ Mpc$^{-1}$.

3. STAR FORMATION TRIGGERED BY GALAXY ENCOUNTERS

In the present work, we upgrade the above model by adding a treatment of flyby events (i.e., encounters that do not lead to bound merging) and of the related bursts of star formation. Indeed, galaxy encounters are expected to destabilize part of the available cool gas by causing it to lose or transfer angular momentum (Barnes & Hernquist 1998; Mihos 1999); this triggers gas inflow. The gas funneled inward may end up in accretion onto central supermassive BHs or in a nuclear starburst (see Sanders & Mirabel 1996). A quantitative model to derive the fraction $f$ of cold gas destabilized by the encounters has been worked out by CV00; here we recall the guidelines in terms suitable for direct implementation in our SAM.

The fraction of cold gas that is destabilized in each interaction event and feeds the starbursts is derived from equation (A3) of CV001 in terms of the variation $\Delta j$ of the specific angular momentum $j \approx Gm/v_d$ of the gas; in slow, grazing encounters between galaxies with relative velocity $V_r$, one obtains

$$f(v, V) \approx \frac{3}{8} \left| \frac{\Delta j}{j} \right| = \frac{3}{8} \left( \frac{m_d}{m} \frac{r_d}{b} \frac{v_d}{V_r} \right).$$  (3)

The effective impact parameter $b = \max \left[ r_d, \sqrt{\bar{d}(V)} \right]$ is the greater of the radius $r_d$ and the average distance $\sqrt{\bar{d}(V)} = R/N_f^{1/3}$ of the galaxies in the halo; we take $V_r$ to be twice the one-dimensional velocity dispersion $\sigma_V = V / \sqrt{2}$ of the host halo. The first approximate equality is derived by considering the amount of gas which is in centrifugal equilibrium outside a
circumnuclear region of fixed size; since the extension $\Delta r$ of the outer region is proportional to $j$ (see, e.g., Mo et al. 1998), a loss of angular momentum implies a negative $\Delta r$ and hence a mass flow toward the circumnuclear region. As for the pre-factor, it accounts for the probability of $1/2$ for inflow rather than outflow as related to the sign of $\Delta j$. We assume that $1/4$ of the inflow feeds the central BH, while the remaining fraction is assumed to kindle circumnuclear starbursts (see Sanders & Mirabel 1996); thus, the starbursts’ efficiency $f$ in equation (3) is 3 times larger than the complementary BH accretion efficiency shown in Figure 1 of Menci et al. (2003).

The last equality in equation (3) has been derived by CV00 by computing the variation $\Delta j = Gm r_d / V b$ of the angular momentum in the galaxy from the gravitational torque (proportional to the disk size $r_d$) exerted by the partner galaxy with mass $m'$; this is time-integrated along the partner orbit. Note that the dependence of $\Delta j$ on $r_d$ causes the amount of destabilized gas to be larger in more massive systems. The average is taken over the probability of finding a galaxy with mass $m'$ in the same halo $V$ where the galaxy $m$ is located.

When inserted into our SAM and applied to the BH accretion and to the related QSO emission (Menci et al. 2003), the above model has proven to be very successful in reproducing the observed properties of the QSO population from $z = 6$ to the present, including the rapid decline of their densities from $z \approx 2.5$ to 0 and even the detailed changes of their LF from $z \approx 5$ to 0. In the present picture, the interaction-driven starbursts constitute the “counterpart” of the BH accretion powering the QSOs.

To compute the average effects of the cold gas destabilization on the star formation rate and hence on the galactic emission, we derive the probability for a given galaxy to be in a burst phase. This is defined as the ratio $\tau_e / \tau_r$ of the duration of the burst to the average time interval between bursts.

In turn, such quantities can be derived from a detailed analysis of the orbital parameters (see Saslaw 1985); following CV00, here we just recall that tides effective for angular momentum transfer (as considered in eq. [3]) require two conditions: the interaction time is to be comparable with the internal oscillation time in the galaxies involved (resonance), and the orbital specific energy of the partners is not to exceed the sum of the specific internal gravitational energies of the partners.

The rate of such encounters is then given by Saslaw (1985) in terms of the distance $r_i \approx 2r$; for a galaxy with given $v$ inside a host halo with circular velocity $V$, the result reads

$$\tau_r^{-1} = n_T(V) \langle \Sigma (v, V) \rangle V_r(V),$$

where $n_T = 3N_T / 4\pi R^3$ and the cross section is averaged over all partners with effective tidal radius $r^*_i$ in the same halo $V$. The membership $N_T$ and the distributions of $v^*$, $r^*_i$, and $V_r$ are computed from the SAM described in § 2.

The condition for a grazing encounter defines the encounter duration $\tau_e = (r_i + r^*_i) / V_r$ (with the upper limit given by $\tau_r$ in eq. [4]) where the average is again over all partners with effective tidal radius $r^*_i$ in the same host halo $V$. It must be noted that the cross section in equation (4) determines the probability for any grazing encounter, including the flyby events, which are in fact more frequent than major mergers and dominate the statistics of galaxy encounters. We also stress that in our model equation (4) determines only the probability $\tau_e / \tau_r$ of finding a galaxy in the burst phase but does not affect the evolution of the galaxy mass function. This is instead determined by the processes of dynamic friction and binary aggregation proper, for which we retain the cross sections given in Menci et al. (2002) and recalled above.

The average SFR associated with the destabilized cold gas during an encounter lasting a time $\tau_e$ reads

$$\Delta \dot{m}_*(v, z) = \left( f(v, V) m_*(v) \right) / \tau_e / \tau_r.$$  

Here the average is over all host halos with circular velocity $V$ and is weighted with the probability $\tau_e / \tau_r$ of finding the galaxy in the burst phase.

We remark that our model includes the effects of both flyby events and bound mergings. Although the former induce starbursts with a lower efficiency ($f \approx 0.1 - 0.4$ at $z \gtrsim 3$), they contribute appreciably to the average star formation rate in bursts (eq. [5]). In fact, flyby events are more probable than major mergers and hence provide larger values for the probability $\tau_e / \tau_r$ entering in the average in equation (5). This holds even though for major merging events (requiring small relative velocities and hence small values of $V_e$ in eq. [3]) the efficiency may attain values of $f \approx 0.7$, consistent with the values 0.65–0.8 obtained in the hydrodynamic simulations by Mihos & Hernquist (1996) and close to the values observed in SCUBA sources and in the local ultraluminous infrared galaxies (see Blain et al. 2002 and references therein; Sanders & Mirabel 1996). At $z \gtrsim 3$, the contributions to equation (5) from merging and from flyby events are comparable.

The average contribution to the stellar emission $S(v, t)$ from bursts in a galaxy with circular velocity $v$ at the time $t$ is given by equation (2), with the quiescent star formation rate $\dot{m}_*$ replaced by the rate of starbursts $\Delta \dot{m}_*(v, t)$ given by equation (5). From $S(v, t)$ we compute the LF given by $N(v, t) dV / dS$.

4. RESULTS

In Figure 1 we show the effect of bursts on the $B$-band LF of galaxies at $z = 0$ and on the UV LFs at $z = 3$ and at 4. Since the emission in the UV (and, to a minor extent, that in the $B$ band) is contributed by massive, short-lived stars, the LFs in Figure 1 show the effect of bursts on the instantaneous star formation at low and high redshifts. At low $z$ (Fig. 1, top), the LFs are little affected by starbursts, whose effect, if anything, is to make the model LF closer to that measured in the Sloan Digital Sky Survey (Blanton et al. 2001).

The predictions for the UV LFs at high $z$ are shown in Figure 1 (middle and bottom), and are compared with data uncorrected for extinction, since the dust absorption is included in the model. In particular, we implemented in our SAM the Milky Way, the Small Magellanic Cloud (SMC), and the Calzetti extinction curves, with the dust optical depth fixed by the fit to the local LF. The related uncertainties in the model predictions are illustrated by showing (for both the quiescent and the starburst modes) the brightest and the faintest LFs (corresponding to the SMC and to the Calzetti curves, respectively). Note that at high $z$ the interactions are more effective in stimulating starbursts; at $z = 4$, compared with the quiescent mode, they brighten the galaxy LF by an amount that grows with the luminosity to reach about 0.7 mag in the brightest magnitude bin. Note also that the inclusion of bursts does not appreciably affect the LFs for galaxies fainter than $M_B \approx -20$.

Indeed, bursts are more efficient in high-mass than in low-mass systems, since the former have larger cross sections for
Formed purely by interactions and hence of the associated starbursts.

Such a picture is born out by Figure 2, where we show the effect of bursts on the cosmic UV luminosity density produced by galaxies and compare it with existing observations. These are based on Hubble Space Telescope and Very Large Telescope imaging surveys aimed at identifying high-$z$ galaxies. The data concerning the UV luminosity density contributed by the bright ($m_{Z} < 25$) galaxy population are compared with the model predictions; we also show the uncertainties due to the different extinction curves, represented as shaded areas. In addition, we compare the recent data from Giavalisco et al. (2004) concerning the density contributed also by fainter galaxies with the lower limit in luminosity provided in the caption.

We note that when the UV luminosity density contributed only by bright ($m_{Z} < 25$) galaxies is considered, the canonical SAMs (with no bursts) underpredict the observed values. This is because such models fail to provide enough star formation to match (once dust is included) the bright end of the UV LFs at $z \approx 4$ (see Fig. 1). However, when one considers the total UV luminosity density (obtained by integrating the LFs over all luminosities), the same models provide a sustained luminosity density (dashed line) up to large $z$. This is because the shape of the LFs from such SAMs are appreciably steeper than the observed ones at high $z$; while such models underpredict the density of bright sources, they overpredict the number of faint galaxies. The two effects balance to yield a sustained total UV luminosity density at high $z$, as shown in Figure 2.

On the other hand, the burst model naturally provides more star formation in massive galaxies and so matches in detail the

![Figure 2](attachment:image.png)

**Figure 2.**—Predicted UV luminosity densities at 1400 Å compared with data. Filled squares refer to the data for galaxies with $m_{Z} < 25$ (Fontana et al. 2003a), while the shaded areas (heavy for the burst model, light for the quiescent model) represent the model predictions, at the same limiting magnitude, adopting different extinction curves in the models (see text). In addition, we plot the UV luminosity density obtained by Giavalisco et al. (2004; open circles) by integrating the observed UV LFs down to 0.2$L_{*}$ (where $L_{*}$ is the characteristic luminosity of observed Lyman break galaxies at $z \approx 3$), compared with the prediction of our model for the same luminosity cut (heavy solid line) averaged over the three extinction curves we considered in the text. We also show the total UV luminosity density in the burst (thin dotted line) and quiescent (thin dashed line) models, averaged over the dust extinction as above.
observed UV luminosity density from bright galaxies with $m_{z} < 25$. We also compare our burst model with the observed UV luminosity density contributed by fainter galaxies. Following the discussion above, any such comparison depends critically on the lower luminosity limit for the integration of the UV LFs. So in comparing our prediction (Fig. 2, heavy solid line) with the data from Giavalisco et al. (2004), we adopt the same luminosity cut used by such authors (see caption), finding a good agreement with observations.

As a result, in the starburst scenario, the fraction of stars predicted to have already formed in massive galaxies by $z \approx 2$ is significantly larger than in the quiescent models. This in turn affects the galaxy LFs and the corresponding redshift distributions in the $K$ band; here the emission is largely contributed by evolved stellar populations, therefore probing the total amount of stars that have been assembled in galaxies by a given cosmic time. In the following, we focus on such issues since, as we recalled in § 1, matching the $K$-band observables and the stellar mass density at intermediate redshifts constitutes one main problem for canonical SAMs.

In Figure 3 we compare our results with observations obtained from the K20 survey (Cimatti et al. 2002; Pozzetti et al. 2003). The starbursts brighten the LF by $\sim$0.5 mag at $z \approx 1.5$, thereby matching the observed shape of the LFs (top). Meanwhile, the faint end of the LFs is left almost unchanged. This is again a consequence of the greater effectiveness of the bursts in more massive galaxies, which is due to the physics of interaction-driven bursts, combined with the statistics of encounters. On the one hand, in each burst galaxies with larger disk sizes undergo larger losses of angular momentum as a consequence of larger gravitational torques, as explained below equation (3); on the other hand, larger galactic sizes favor the encounters, as described in detail below equation (4). Correspondingly, the burst model matches the observed number of luminous ($m_{K} < 20$) galaxies at $z \approx 1.5$, while the quiescent model underpredicts the number by a factor of $\sim$3-4 (see Fig. 3, bottom).

Inspection of Figure 3 shows that our burst model provides a better fit to the observed $z$-distribution of galaxies with $m_{K} < 20$ than does the SAM by Somerville et al. (2001), which also included starbursts. The reason is that our model provides a higher star formation rate at high redshift. This is shown by the dotted line in Figure 2; when the total UV luminosity density of our model is converted to a total density of star formation, the resulting star formation rate is larger than the Somerville et al. (2001) rate at $z > 4$ for any reasonable dust extinction adopted in the conversion. The improvement is achieved despite an average value of the burst efficiency $f_{\text{burst}}$ somewhat lower than that adopted by Somerville et al. (2001).

Our improvement is due to two circumstances. First, the above authors associate starbursts only with bound mergers; for such events (requiring very slow encounters with small $V_r$), we obtain from equation (3) values ($f \approx 0.7$) comparable to theirs, as these particular interactions are maximally effective in inducing loss of gas angular momentum. However, in our model we also consider the effect of the more frequent flyby events that do not lead to outright merging of the involved galaxies. These produce starbursts with a lower efficiency $f \approx 0.1-0.4$ (at $z \geq 3$) but dominate the encounter statistics. While they yield a low average $f$, the key quantity for $\Delta m$, is instead the product $f r_{-1}^3$ (i.e., the efficiency weighted with the interaction rate), which is enhanced by the flyby events; see equation (5) and the discussion below it. Second, the dynamics of subhalo mergers in our model slightly favors the formation of massive galaxies at high $z$ compared to Somerville et al. (2001). This is because the cross section that we adopt for bound mergers (taken from Menci et al. 2002, eq. [4]) is somewhat larger than that used by Somerville et al. (2001), especially at high $z$. In fact, the above authors adopt the cross section derived by Makino & Hut (1997) from N-body simulations, strictly valid for encounters between equal galaxies in the limit of large relative velocities. Our cross section, although reducing to Makino & Hut’s (1997) in the proper limit of merging between equal galaxies with large $V_r$ (as shown in Menci et al. 2002), also holds for lower relative velocities. This is particularly relevant at high $z \geq 4$, when galaxies reside in environments with low velocity dispersions.

The enhancement in the fraction of stars formed in massive galaxies at high redshift $z > 3$ due to our treatment of the bursts is illustrated by Figure 4. There we show for both the burst and the quiescent modes the evolution of the stellar mass density in massive ($10^{10} M_{\odot} < m_{*} < 10^{11} M_{\odot}$) systems and compare it with various observations. Although the present data are not sufficient by themselves to discriminate between the two models, the plot clearly shows that at $z \approx 2$ the model with bursts predicts a fraction of stars formed in massive systems that is 2.5 times larger than that predicted by the quiescent models.

5. CONCLUSIONS

We have presented the results of a SAM that includes a physical model for starbursts. The latter originate from the

![Image](https://via.placeholder.com/150)

**Fig. 3.** Top: $K$-band galaxy LFs at $z = 1.5$ in the quiescent (dashed line) and starburst (solid line) models compared with the data from the K20 survey (Pozzetti et al. 2003). Bottom: Corresponding cumulative $z$-distributions of $m_{K} < 20$ galaxies are compared with observations from the K20 survey (Cimatti et al. 2002). The inset shows in detail the cumulative distribution in the range $1 < z < 3$ with the $3 \sigma$ Poissonian confidence region (shaded area); the dotted line reproduces from Cimatti et al. (2002) the prediction of the SAM by Somerville et al. (2001).
destabilization of cold galactic gas occurring in galaxy encounters as described by Cavaliere & Vittorini (2000). In this scenario, part of the destabilized gas feeds the accretion onto BHs powering the QSOs (see Menci et al. 2003), while the complementary larger fraction produces circumnuclear starbursts at redshifts $z \approx 2$–4, preferentially in massive objects. This speeds up the star formation in massive galaxies (favored by their larger cross sections for encounters) at high redshifts (when the higher densities and the slower relative velocities of galaxies in common halos favor strong interactions). The LFs resulting from our model match those of luminous ($M_B < -21$) Lyman break galaxies observed at $z \approx 3$ and 4, while leaving almost unchanged the model predictions for fainter objects. Thus, at $z \approx 2$, a larger fraction of the stellar content of the massive galaxies is already in place, at variance with the predictions of previous hierarchical models; the resulting $K$-band LFs and $z$ distributions match the existing data.

Compared to Somerville et al. (2001), our model gives qualitatively similar results but a better fit (see Fig. 3) to the observed $z$-distribution of bright $K > 20$ galaxies at $z \gtrsim 1.5$. Such a large rate is mainly due to the novel inclusion of flyby events which, although producing starbursts with lower efficiency ($f \approx 0.1$–0.2 at $z \approx 3$), are more frequent than the bound merging events. In our scenario, the UV luminosity, and hence the star formation rate, of massive galaxies at high redshift is in part contributed by the few powerful starbursts occurring in major merging events, and in part by a more widespread, although less powerful, brightening of galaxies almost continuously stimulated by the frequent encounters. In this regime, a considerable fraction, close to 0.25, of the present stellar content of massive ($10^{10} M_\odot < m < 10^{11} M_\odot$) galaxies is formed by $z = 2$ (see Fig. 4). As a result, at lower redshifts ($z \approx 1.5$), a considerable fraction of massive galaxies contain a stellar population evolved enough to provide the bright $K$-band luminosities required to match the observed LFs and counts. In summary, we have shown that making early massive galaxies takes not only the early collapse of large DM halos favored in the $\Lambda$CDM cosmology, but also the starlight emitted by baryons as a result of galaxy interactions.

We stress that our results are achieved on the basis of a physical, rather than a phenomenological, model to derive the burst rate and the amount of cold gas converted into stars during the bursts. Moreover, our model naturally connects with the accretion onto BHs and with the corresponding QSO emission. Such a unified description is thus able to link the independent observations concerning the luminosity distributions of QSOs and galaxies.

For $z < 2$, the merging and the encounter rates decline and no longer affect the evolution of the cold gas reservoirs of massive galaxies. Therefore, these galaxies specifically enter a phase of nearly passive evolution, with redder colors that in some cases—whose probability we shall give in detail elsewhere—correspond to those of many observed extremely red objects (EROs; see, e.g., Daddi, CIMatti, & Renzini 2000 and references therein). In our model, the beginning and the development of such a phase is naturally matched to the dramatic drop of the QSO luminosities; these are entirely triggered by the gas destabilized in the encounters, and so are particularly sensitive to the current merging and interaction rates of their host galaxies.

We thank the referee for useful comments which helped to improve our paper.

REFERENCES

Barnes, J. E., & Hernquist, L. E. 1998, ApJ, 495, 187
Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., & Frayer, D. 2002, Phys. Rep., 369, 111
Blanton, M. R., et al. 2001, AJ, 121, 2358
Bruzual, A., & Charlot, S. 1993, ApJ, 405, 538
Cavaliere, A., & Menci, N. 1993, ApJ, 407, L9
Cavaliere, A., & Vittorini, V. 2000, ApJ, 543, 599 (CV00)
Cimatti, A., et al. 2002a, A&A, 391, L1
Cole, S., Lacey, C. G., Baugh, C. M., & Frenk, C. S. 2000, MNRAS, 319, 168
Daddi, E., CIMatti, A., & Renzini, A. 2000, A&A, 362, L45
Dickinson, M., Papovich, C., Ferguson, H. C., & Budavari, T. 2003, ApJ, 587, 25
Fontana, A., Menci, N., D’Odorico, S., Giallongo, E., Poli, F., Cristiani, S., Moorwood, A., & Saracco, P. 1999, MNRAS, 310, L27
Fontana, A., Poli, F., Menci, N., Nonino, M., Giallongo, E., Cristiani, S., & D’Odorico, S. 2003a, ApJ, 587, 544
Fontana, A., et al. 2003b, ApJ, 594, L9
Giavalisco, M., et al. 2004, ApJ, 600, L103
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Lacey, C., & Cole, S. 1993, MNRAS, 262, 627
Liu, J., & Hut, P. 1997, ApJ, 481, 83
Menci, N., Cavaliere, A., Fontana, A., Giallongo, E., & Poli, F. 2002, ApJ, 575, 18
Menci, N., Cavaliere, A., Fontana, A., Giallongo, E., Poli, F., & Vittorini, V. 2003, ApJ, 587, L63
Mihos, J. C. 1999, ApSS, 266, 195
Mihos, J. C., & Hernquist, L. 1996, ApJ, 464, 641
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
Pozzetti, L., et al. 2003, A&A, 402, 837
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Sanders, D. B., & Mirabel, I. F. 1996, ARA&A, 34, 749
Saslaw, W. C. 1985, Gravitational Physics of Stellar and Galactic Systems (Cambridge: Cambridge Univ. Press)
Somerville, R. S., & Primack, J. R. 1999, MNRAS, 310, 1087
Somerville, R. S., Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1