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DIFFUSE STELLAR COMPONENT IN GALAXY CLUSTERS AND THE EVOLUTION OF THE MOST MASSIVE GALAXIES AT $z \lesssim 1$

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ABSTRACT

The high end of the stellar mass function of galaxies is observed to have little evolution since $z \sim 1$. This represents a stringent constraint for merger-based models, aimed at explaining the evolution of the most massive galaxies in the concordance ΛCDM cosmology. In this Letter we show that it is possible to remove the tension between the above observations and model predictions by allowing a fraction of stars to be scattered to the diffuse stellar component (DSC) of galaxy clusters at each galaxy merger, as recently suggested by the analysis of *N*-body hydrodynamical simulations. To this purpose, we use the MORGANA model of galaxy formation in a minimal version, in which gas cooling and star formation are switched off after $z = 1$. In this way, any predicted evolution of the galaxy stellar mass function is purely driven by mergers. We show that, even in this extreme case, the predicted degree of evolution of the high end of the stellar mass function is larger than that suggested by data. Instead, the assumption that a significant fraction, ~30%, of stars are scattered in the DSC at each merger event leads to a significant suppression of the predicted evolution, in better agreement with observational constraints, while providing a total amount of DSC in clusters, which is consistent with recent observational determinations.

Subject headings: cosmology: theory — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation

On-line material: color figures

1. INTRODUCTION

The ΛCDM model provides the standard framework to study the formation of cosmic structures, with only residual uncertainties on the values of cosmological parameters. However, while consensus on the agreement between model and data is reached for observables that probe the large-scale structure of the universe (e.g., Springel et al. 2006), the situation becomes far less clear when the formation and evolution of galaxies are addressed. In this case the underlying astrophysical processes at play are so complex and poorly understood that it is very difficult to disentangle the cosmologically driven building of structure from the effects of such processes.

At variance with the behavior of dark matter (DM) halos, the building of galaxies shows a "downsizing" or "antihierarchical" behavior; at low redshift the specific star formation rate is higher for smaller galaxies, while more massive galaxies show higher specific star formation rates at higher redshift (see, e.g., Cowie et al. 1996; Bundy et al. 2006). Besides, stars in more massive objects appear to have formed, on average, earlier than those in less massive ones (see, e.g., Treu et al. 2005; Thomas et al. 2005). While for the bulk of galaxies this behavior can be explained as due to the effect of stellar or active galactic nucleus (AGN) feedback (see, e.g., Croton et al. 2006; Bower et al. 2006), the nearly passive evolution of the most massive galaxies highlights a possible paradox of present models of galaxy formation. More specifically, galaxies with stellar masses ~10^{12} $M_\odot$ show a remarkably constant number density out to redshift $z \sim 1$ (see, e.g., Fontana et al. 2004; Drory et al. 2005; Yamada et al. 2005; Zucca et al. 2006; Caputi et al. 2006; Bundy et al. 2006; Fontana et al. 2006; Wake et al. 2006; Cimatti et al. 2006; Brown et al. 2006; but see also Bell et al. 2004; Faber et al. 2005). These exceptionally massive galaxies are the giant ellipticals that typically represent the dominant galaxies of rich galaxy groups and clusters. Furthermore, galaxy clusters are the most massive DM halos at low redshift and are predicted and observed to still be undergoing a phase of significant merger events. The massive ellipticals that reside at the centers of two merging clusters are predicted to merge after one dynamical friction time, which is of order of 1 Gyr. This leads to two important consequences, namely, an evolution of the stellar mass function, which is constrained by data, and mergers between big ellipticals. These are not associated to starbursts, due to the lack of cold gas supply in the merging galaxies ("dry mergers") and are rather difficult to observe (van Dokkum 2005; Masjedi et al. 2006; Bell et al. 2006).

On the other hand, galaxy clusters are pervaded by a diffuse stellar component (DSC), which only in part can be associated with the extended halo of a dominant cD galaxy. These stars are usually not accounted for in the census of the stellar mass budged in clusters. Their number and mass can be estimated by observing intracluster planetary nebulae (Arnaboldi et al. 2002, 2004; Feldmeier et al. 2003, 2004a; Castro-Rodríguez et al. 2003; Gerhard et al. 2005) intracluster novae and supernovae (Gal-Yam et al. 2003; Neill et al. 2005), asymptotic giant branch stars (Durrell et al. 2002) using surface photometry of single clusters (Gonzalez et al. 2000; Feldmeier et al. 2002, 2004b; Adami et al. 2005; Krick et al. 2006), or by measuring the diffuse light in co-added images of many galaxy clusters (Zibetti et al. 2005). These observations give fractions of total luminosity contributed by the DSC ranging from 10% to 40% in massive clusters. The relatively poorer Virgo and Fornax Clusters have observed fractions of about 10% (Feldmeier et al. 2003; Durrell et al. 2003; Neill et al. 2005; Mihos et al. 2005), thus suggesting an increasing DSC fraction with cluster richness (see also Lin & Mohr 2004). The origin of the DSC

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in galaxy clusters has been studied with the aid of N-body simulations (Napolitano et al. 2003; Murante et al. 2004; Willman et al. 2004; Sommer-Larsen et al. 2005; Rudick et al. 2006; Stanghellini et al. 2006), reaching the general conclusion that a DSC is naturally expected to arise from the hierarchical assembly of clusters. In particular, Murante et al. (2006) showed that 60%–90% of the DSC is generated at $z < 1$, and only a minor part of it is due to tidal stripping, the rest being contributed by relaxation processes during galaxy mergers.

Clearly, the possibility that a significant amount of stars are diffused into the DSC during the low-redshift "dry assembly" of the most massive ellipticals has important consequences for the evolution of the high-mass end of the galaxy stellar mass function. Massive galaxies at the center of clusters contain a significant fraction of the total stellar mass of the cluster, ranging from 10% to 30% for poor clusters ($M_h \sim 10^{14}\ M_\odot$) to 5%–10% for rich ones ($M_h \sim 10^{15}\ M_\odot$; see, e.g., Lin & Mohr 2004). If at each merger these galaxies lost a fair fraction of their stars to the DSC component, and if this mechanism were responsible for the buildup of most of the DSC, then this process would limit the mass growth of the central galaxy by mergers since $z \sim 1$.

In this Letter we show, using the results of N-body simulations and the MORGANA galaxy formation model (Monaco et al. 2006), that the evolution of massive galaxies driven by mergers is severely constrained by observations, and that this tension is removed if a significant fraction of stars is lost to the DSC at each merger. Once this effect is taken into account, we predict a much slower evolution of the high end of the stellar mass function at $z \lesssim 1$, while producing an amount of DSC at $z \sim 0$ that is consistent with current observational limits. In this Letter we use a cosmology with $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.04$, $H_0 = 70$ km s^{-1} Mpc^{-1}, and $\sigma_8 = 0.9$; none of the results depends sensitively on any of these parameters.

2. BUILDING OF THE DIFFUSE STELLAR COMPONENT

Murante et al. (2004, 2006) analyzed hydrodynamical simulations of galaxy clusters, performed with the GADGET-2 code (Springel 2005), which include the processes of star formation and supernova feedback. They found that the DSC represents a significant fraction of the stellar population in clusters, approximately ranging from 10% to 40%, with an increasing trend with cluster mass (see Fig. 1, *blue points*), thus in keeping with observational results. Murante et al. (2006) also shows that the bulk of the DSC is not due to tidal stripping of noncentral galaxies, which accounts for no more than 5%–10% of the total stellar component, but to relaxation processes taking place during the dry mergers leading to the buildup of the central dominant galaxy. As a result, up to ~30% of the stellar mass of the merging galaxies becomes unbound to the resulting central galaxy. In terms of the mass of each merging satellite, this translates to 10%–50% of its mass that is scattered to the DSC, depending on the mass ratio of the merging galaxies.

In this Letter we resort to the novel MORGANA model of galaxy formation to quantify the effect of including the generation of a DSC at each merger on the evolution of the stellar mass function. This code has been shown to be able to reproduce the buildup of the massive galaxies (Fontana et al. 2006) and the population of AGNs (Fontanot et al. 2006). For the purpose of the present analysis, MORGANA has been modified by switching off gas cooling and star formation at $z < 1$. In this way, we minimize the evolution of the stellar mass function, which is then driven only by mergers. Furthermore, we implement the generation of the DSC as follows: (1) tidal stripping of stars is applied to satellite galaxies[6] and (2) when the satellite merges with the central galaxy, a fraction $f_{\rm scatter}$ of its stars are scattered to the DSC. Prescription (2) is at variance with Monaco et al. (2006), where scattering is allowed only in major mergers. Such a recipe, inspired by the results of Murante et al. (2006), is deliberately simplified, and we use it here to provide a qualitative picture of the effect of including the production of the DSC into our model.

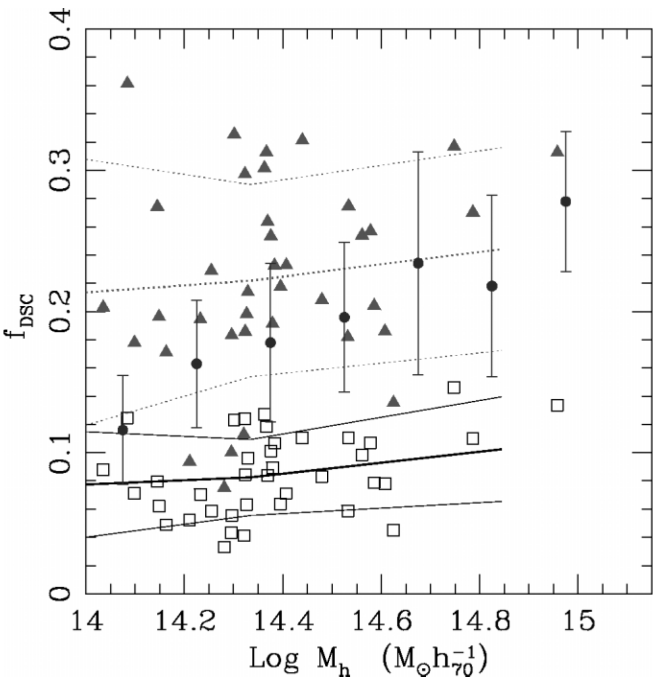

FIG. 1.—Fraction of stars in diffuse stellar component for model DM halos with $M_h > 10^{14}\ M_\odot$. The open squares refer to the expectation of MORGANA with only tidal stripping ($f_{\rm scatter} = 0$), the filled triangles to the case $f_{\rm scatter} = 0.3$. The solid and dotted lines give the average (*thick lines*) and $\pm 1\ \sigma$ (*thin lines*) location of the points. For comparison, we show the results from simulations by Murante et al. (2006) as circles with error bars, which represent the rms scatter within different mass intervals. [*See the electronic edition of the Journal for a color version of this figure.*]

In Figure 1 we compare the fraction of DSC, $f_{\rm DSC}$, as a function of cluster mass, found in the simulations analyzed by Murante et al. (2004) and predicted by MORGANA for both $f_{\rm scatter} = 0$ and 0.3. MORGANA predictions have been computed for 37 clusters, with mass $M_{\rm H} > 10^{14}\ M_\odot$, identified in a 150 Mpc box where the DM clustering is sampled with 512^3 particles. This comparison shows that using a fixed value of $f_{\rm scatter}$ produces a milder dependence of $f_{\rm DSC}$ on the cluster mass, thus confirming that our approach of introducing the effect of the DSC generation is oversimplified. Still, predictions from the semianalytical model and from the hydrodynamical simulations share several common features. For instance, tidal stripping is confirmed to bring only ~10% of the total stellar mass to the DSC, with $f_{\rm scatter} \sim 0.3$ required to better account for simulation results. Quite interestingly, we also verified that ~70% of the DSC is generated at $z \lesssim 1$ by both MORGANA and simulations. On the basis of these results, we conclude that the MORGANA model can be used to test the effect of the DSC generation on the evolution of the high end of the galaxy stellar mass function.

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[6] At the time of first periastron of the satellite orbit in the host DM halo, all the stars that lie beyond the tidal radius (according to the unperturbed profile of the galaxy) are moved to the DSC.

3. RESULTS AND DISCUSSION

As mentioned in § 1, the population of massive galaxies with $M_\star \sim 10^{11}\ M_\odot$ shows a modest but significant degree of evolution since $z \sim 1$. Using the GOODS-MUSIC sample, Fontana et al. (2006) found this evolution to amount to a factor of 2.5 in mass density, a degree of evolution that has been shown to be consistent with the predictions of MORGANA. On the other hand, very massive galaxies with $M_\star \sim 10^{12}\ M_\odot$ show a much lower degree of evolution. We use here as a convenient quantification of this evolution the logarithmic increase of $M_{-4.5}$, the stellar mass at which the stellar mass function reaches the level $\Phi(\log M) = 10^{-4.5}$ Mpc^{-3}, from $z = 1$ to 0. A detailed discussion on how to measure this quantity from data is beyond the scope of this Letter. Using data from Yamada et al. (2005), Drory et al. (2005), Bundy et al. (2006), Cimatti et al. (2006), Fontana et al. (2006), and Brown et al. (2006), we infer that the evolution of $M_{-4.5}$ between $z = 1$ and 0 cannot be larger than 0.2 dex. This modest evolution clearly requires that massive galaxies must have had a small net gain in stellar mass during the last 7 Gyr.

To test the consistency of this constraint with the expected evolution of massive galaxies, we use the MORGANA model as follows. We follow the evolution of the galaxy population until $z = 1$, assuming the standard choice of parameters used in both Monaco et al. (2006) and Fontana et al. (2006) with[7] $f_{\rm scatter} = 0$. We then finetune AGN feedback[8] to reproduce almost exactly the analytic fit of the $z = 1$ stellar mass function proposed by Fontana et al. (2006). Figure 2 shows the predicted mass function at $z = 1$ (*dashed line*), compared to the GOODS-MUSIC estimate in the redshift range 0.8–1.3; the shaded region, bound by the analytic fit of the observed stellar mass function at $z = 1$ and the same curve shifted in mass by 0.2 dex, highlights the allowed range of the high end at $z = 0$. The model is known to overestimate at $z = 1$ the number density of smaller objects ($M_\star \lesssim 10^{11}\ M_\odot$; Fontana et al. 2006), and this is noticeable in the figure. As already mentioned in § 2, we then compute the evolution of the galaxy population at $z < 1$ by switching off all the astrophysical processes, including cooling, star formation, feedback, galactic winds and superwinds, so that galaxies can grow only by mergers. The solid line in the upper left panel of Figure 2 shows the results of this model for $f_{\rm scatter} = 0$: we obtain $\Delta \log M_{-4.5} \simeq 0.3$, i.e., the mass of the most massive galaxies grows by more than a factor of 2, in line with the results by De Lucia et al. (2006) and De Lucia & Blaizot (2006), but at variance with respect to observational results.

This result highlights the presence of a potential paradox in cosmological models of galaxy formation: even under the assumption that mergers only drive the evolution of the galaxy population at $z < 1$, model predictions still provide too strong an evolution of the high end of the stellar mass function. This conclusion is robust against possible uncertainties in the dynamical friction timescales, which determine the difference between the timing of DM halo merging and galaxy merging. We verified that, since these timescales are much smaller than the Hubble time, an uncertainty in their estimate does not significantly influence the final results.

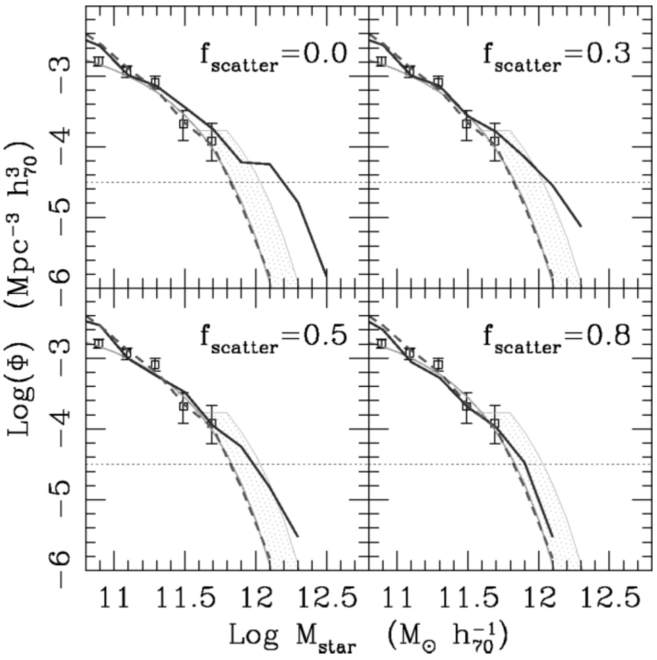

FIG. 2.—Evolution of the stellar mass function from $z = 1$ to 0. In all panels, observational data points are from GOODS-MUSIC (Fontana et al. 2006) and refer to the stellar mass function in the redshift range 0.8–1.3; the solid line gives the best fit proposed by the same authors at $z = 1$. The shaded region highlights the allowed evolution of the high end of the stellar mass function by 0.2 dex. The dashed line gives the model results at $z = 1$, computed assuming $f_{\rm scatter} = 0$ and finetuned to reproduce very accurately the analytic fit at the same redshift, while the solid line gives the prediction at $z = 0$, computed switching off all astrophysical processes (cooling, star formation, and feedback) and setting $f_{\rm scatter}$ to the value specified in the panel. The thin dotted horizontal line marks the level $10^{-4.5}$ Mpc^{-3} that is used to quantify the evolution of the stellar mass function. [*See the electronic edition of the Journal for a color version of this figure.*]

As already discussed in § 2, the model with $f_{\rm scatter} = 0$ also underestimates the fraction of DSC produced in simulations for the most massive clusters (see Fig. 1). The other three panels of Figure 2 show the evolution of the stellar mass function for values of $f_{\rm scatter} = 0.3$, 0.5, and 0.8. Values between 0.3 and 0.5 are sufficient to suppress $\Delta \log M_{-4.5}$ to below 0.2 dex and at the same time reproduce the observed fraction of DSC. The rather extreme value of $f_{\rm scatter} = 0.8$ instead tends to overproduce the DSC.

From these results we conclude that the observed modest evolution of the high-mass tail of the stellar mass function can be reconciled with model predictions by allowing a significant fraction of the stellar mass to be scattered away from the galaxies and disperse into the DM halo. This is also shown in Figure 3, where the results of the models are reported in the ($f_{\rm DSC}$, $\Delta \log M_{-4.5}$)-plane as lower limits to the values that would be obtained with a full treatment of baryon physics. The shaded area shows the region currently allowed by data. As a word of caution, we remind that a direct comparison between the theoretical and observational estimates of the DSC fraction is quite delicate. Theoretical estimates are affected by numerical effects and by uncertainties in the modeling of complex baryon physics that give rise to galaxies, while observational estimates depend on a number of hypothesis linking the observables (e.g., number of intracluster planetary nebulae, ratio of fluxes from the DSC and from galaxies) to the volume-averaged $f_{\rm DSC}$.

Despite all these uncertainties, we regard our result as a robust one. The details of the galaxy formation models are immaterial in this test as long as the model gives a plausible population of

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[7] This is done in order to have all models starting from the same configuration at $z = 1$. As in MORGANA ~70% of the DSC is created at $z < 1$, we correct our $f_{\rm DSC}$ values by multiplying them by 1/0.7.

[8] The fine-tuning is performed by setting the $f_{\rm jet,0}$ parameter to 2 in place of 1 and assuming the "forced quenching" procedure; see Monaco et al. (2006) for details.

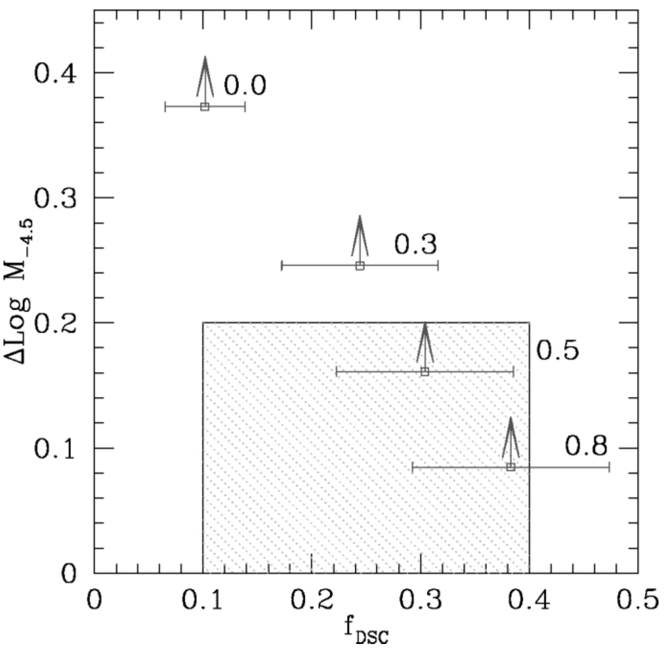

FIG. 3.—Comparison of model and observations in the ($f_{\rm DSC}$, $\Delta \log M_{-4.5}$)-parameter space. It shows the relation between the production of DSC and the evolution of the stellar mass function at the fixed number density of $10^{-4.5}$ Mpc^{-3}. The shaded area gives the rough observational constraints reported in this Letter ($\Delta \log M_{-4.5} < 0.2$ and $0.1 < f_{\rm DSC} < 0.4$); the points refer to the model with the four values of $f_{\rm scatter}$ (reported beside the relative points) given in Fig. 2. We consider these points to be lower limits (see text). [*See the electronic edition of the Journal for a color version of this figure.*]

massive galaxies at $z \sim 1$ and describes correctly the merging of galaxies driven by the hierarchical assembly of DM halos. In our calculation the evolution to $z = 0$ can only be underestimated, since it is performed by forcing a complete quenching of cooling and star formation. This is clearly seen in Figure 2, where the population of galaxies with $M_\star \sim 10^{11}\ M_\odot$ is underestimated at $z = 0$. As a consequence, the evolution predicted by mergers is an underestimate as well, as it does not include the stars formed since $z = 1$. In this case the known excess of small galaxies predicted at $z = 1$ (Fontana et al. 2006) gives a modest bias, which is in the opposite direction with respect of the more important bias obtained by quenching any evolution of the stellar component. Therefore, it does not hamper our conclusions by any means.

In conclusion, we have shown that the modest evolution of the high-mass end of the stellar mass function may highlight a problem for current models of galaxy formation in the ΛCDM framework. On the other hand, the presence of a significant DSC in galaxy clusters and the mild evolution of the high end of the galaxy stellar mass function may both point toward a scenario in which a significant fraction of the stellar mass of galaxies becomes unbound at each merging event, thereby suppressing the merger-driven evolution. Solving this problem requires that a significant fraction, >20%, of the total stellar budget in rich galaxy clusters must be in the form of a diffuse component. Deeper searches of intracluster light are necessary to either confirm or dispute this prediction. Future instruments, like the Large Binocular Camera at LBT or *JWST*, will provide a quantum leap in the census of the diffuse stars in the near future.

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