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THE IMPORTANCE OF SPHEROIDAL AND MIXED MERGERS FOR EARLY-TYPE GALAXY FORMATION

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ABSTRACT

We use semianalytical modeling techniques to investigate the progenitor morphologies of present-day elliptical galaxies. We find that, independent of the environment, the fraction of mergers of bulge-dominated galaxies (early types) increases with time. The last major merger of bright present-day elliptical galaxies with $M_B \lesssim -21$ was preferentially between bulge-dominated galaxies, while those with $M_B \sim -20$ have mainly experienced last major mergers between a bulge-dominated and a disk-dominated galaxy. Independent of specific model assumptions, more than 50% of present-day elliptical galaxies in clusters with $M_B \lesssim -18$ had major mergers that were not of spiral galaxies, as usually expected within the standard merger scenario.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: interactions — methods: numerical

1. INTRODUCTION

The formation of elliptical galaxies by merging disk galaxies has been studied in numerous simulations since it was proposed by Toomre & Toomre (1972; see Barnes & Hernquist 1992 and Burkert & Naab 2003 for reviews). This merging hypothesis has proved to be very successful in explaining many of the properties of elliptical galaxies. Even though there are still questions that need further investigation, like the origin of peculiar core properties of elliptical galaxies, it is now widely believed that elliptical galaxies were formed by mergers of disk galaxies. In the framework of hierarchical structure formation, merging is the natural way in which structure grows. Indeed, the observed merger fraction of galaxies is in agreement with the predictions of hierarchical models of galaxy formation (Khochfar & Burkert 2001). Semianalytical models (SAM) of galaxy formation, which successfully reproduce many observed properties of galaxies, generally assume that star formation takes place in a disk that formed by gas infall into dark matter halos (e.g., White & Frenk 1991; Kauffmann et al. 1999; Somerville & Primack 1999; Springel et al. 2001). Once these disk galaxies merge, depending on the mass ratio of the galaxies, elliptical galaxies form. *N*-body simulations suggest a mass ratio of $M_1/M_2 \leq 3.5$, with $M_1 \geq M_2$ to generate elliptical galaxies (Naab & Burkert 2001). We refer to these events as major mergers, and we refer to events with $M_1/M_2 > 3.5$ as minor mergers. Elliptical galaxies can then build up new disks by accretion of gas and become bulges of spiral galaxies (e.g., Steinmetz & Navarro 2002) or merge with other galaxies. Up to now, the frequency of elliptical-elliptical mergers (spheroidal mergers, E-E) or spiral-elliptical mergers (mixed mergers, Sp-E) has not been studied in detail despite observational evidence indicating their importance. Van Dokkum et al. (1999), for example, find mergers of red, bulge-dominated galaxies in a rich cluster at intermediate redshifts.

In this Letter, we investigate the likelihood of spheroidal and mixed mergers. Our semianalytical model was constructed similar to those described in detail by Kauffmann et al. (1999) and Springel et al. (2001). Merger trees of dark matter halos with different final masses M_0 at $z = 0$ were generated using the method described by Somerville & Kolatt (1999), which is based on the extended Press-Schechter formalism (Bond et al. 1991; Bower 1991). The mass M_0 traces different environments. We adopt $M_0 = 10^{15}\ M_\odot$, which represents an environment typical for clusters of galaxies. We also tested low-density environments that correspond to $M_0 = 10^{12}\ M_\odot$ and found no significant difference besides the fact that galaxies become more massive in environments with large M_0. Present-day elliptical galaxies are identified by their *B*-band bulge-to-disk ratio as in Springel et al. (2001), which corresponds to roughly more than 60% of the stellar mass in the bulge. We divide the progenitor morphologies into two distinct classes. Those with a dominant bulge component are labeled "E" and those with a dominant disk component are labeled "Sp." In what follows, our standard model assumes that the stars of accreted satellites in minor mergers contribute to the bulge component of the more massive progenitor and that bulge-dominated galaxies have more than 60% of their stellar mass in the bulge. We adopt a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65$ km s^{-1} Mpc^{-1}.

2. MORPHOLOGY OF PROGENITORS

We start by analyzing the morphology of progenitors involved in major mergers adopting our standard model. Due to continuous interactions, the fraction of bulge-dominated galaxies increases with decreasing redshift. As a result, the probability for them to be involved in a major merging event increases too, which is shown in the upper left-hand graph of Figure 1 for a cluster environment ($M_0 = 10^{15}\ M_\odot$). In the lower left-hand graph, the enhanced probability δ_P, defined as the ratio of the probability of mergers with certain morphologies found in the SAM to the probability of randomly drawing two galaxies from the existing sample of galaxies, is shown. Mergers of type E-E and Sp-E occur more frequently than expected if chosen randomly from the apparent population of galaxies. Only Sp-Sp mergers are nearly as frequent as in the random sample. At redshifts $z \leq 1$, δ_P increases for E-E and Sp-E mergers, while it decreases for Sp-Sp mergers. If one assumes δ_P to be inversely proportional to the correlation length r_0 of galaxies with certain morphologies, our results indicate a decrease with redshift in r_0 for early-type galaxies and an increase for late-type galaxies, which is consistent with the observed trend (e.g., Phleps & Meisenheimer 2003). The most massive galaxies are mainly bulge-dominated (e.g., Binney & Merrifield 1998; Kochanek et al. 2001), suggesting that the fraction of E-E and Sp-E is mass-dependent. The right panels of Figure 1 illustrate the fraction of

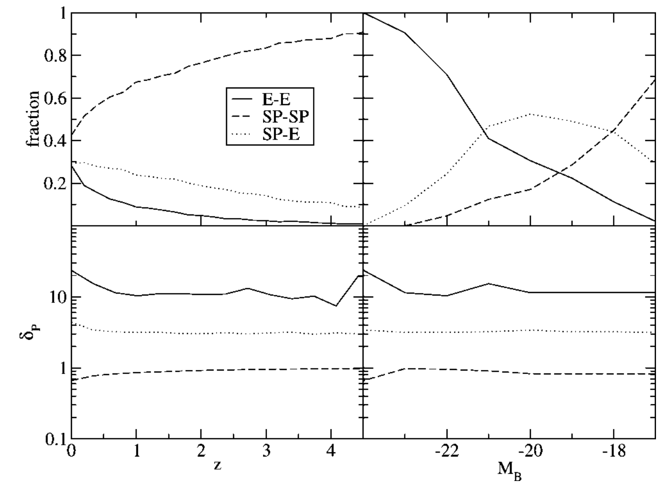

FIG. 1.—*Left panels*: Fraction of major mergers between galaxies of different morphology at each redshift. The lower graph shows the enhanced probability δ_P of having a merger between a galaxy pair of given morphological type with respect to the probability of a merger of the same type choosing galaxies randomly from the existing galaxy population. *Right panels*: Fraction of present-day elliptical galaxies that experienced a most recent major merger of type Sp-Sp, E-E, or Sp-E as a function of their *B*-band magnitude. The lower graph shows δ_P at the average epoch of the most recent major merging as a function of the elliptical galaxies' present-day magnitude. Results are shown for the standard model.

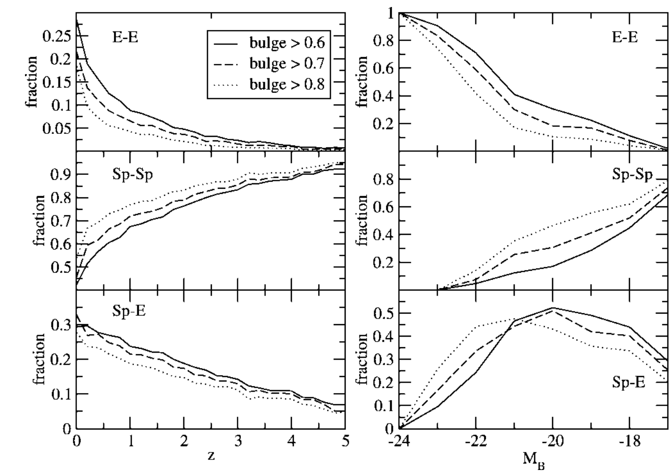

FIG. 2.—*Left panels*: Dependence of merger fractions of different types on the definition of bulge-dominated galaxies. *Right panels*: Same dependence, but for the last major merger type of present-day elliptical galaxies at each *B*-band magnitude. Results are shown for a cluster environment of $M_0 = 10^{15}\ M_\odot$ and a model in which all the satellite stars from minor mergers contribute to the bulge of the more massive merger partner.

present-day elliptical galaxies at each magnitude that experienced most recent major mergers of type E-E, Sp-Sp, or Sp-E. The fraction of E-E and Sp-E mergers indeed increases toward brighter luminosities, with a tendency to increase faster in more dense environments, because of the higher fraction of bulge-dominated galaxies. One can distinguish three luminosity regions: (1) $M_B \lesssim -21$ for spheroidal mergers, (2) $M_B \sim -20$ for mixed mergers, and (3) $M_B \gtrsim -18$ for Sp-Sp mergers. The enhanced probability remains roughly constant in the different regions, showing only a slight increase in the E-E fraction and a decrease in the Sp-Sp fraction at the bright end. This trend is not too surprising since in the hierarchical merging scenario, massive objects form last.

It is important to understand how our results depend on the model assumptions. We focus on cluster environments with $M_0 = 10^{15}\ M_\odot$, where the fraction of elliptical galaxies is largest, and we investigate the dependence on our definition of a bulge-dominated galaxy. We varied the definition of a bulge-dominated galaxy from more than 60% mass in the bulge component to more than 80% mass in the bulge. The results are shown in Figure 2. The tighter definition of a bulge-dominated galaxy reduces (increases) the fraction of E-E (Sp-Sp) mergers at all redshifts, which results in a lower (higher) fraction of the most recent major mergers being bulge (disk) dominated galaxies. The right panels of Figure 2 reveal in which mass range the galaxies are most sensitive to the definition of a bulge-dominated galaxy. At the high-mass end with $M_B \lesssim -21$ (E-E region), most of the E-progenitors have a very large fraction of their mass in their bulge component, while in the Sp-E and Sp-Sp regions, the E-progenitors do not have such dominant bulge components, which explains why the Sp-E fraction increases for $M_B \lesssim -21$ if a tighter definition of bulge-dominated galaxies is assumed.

In our standard model, we assumed that the stars of a satellite in a minor merger contribute to the bulge component of the more massive progenitor. However, the fate of the satellite's stars is not that clear; e.g., Walker, Mihos, & Hernquist (1996) find that in mergers with $M_1/M_2 = 10$, the stars of the satellite get added in roughly equal parts to the disk and the bulge. We tested three different models, assuming that the stars of satellites in minor mergers contribute to the bulge (bulge model; e.g., Kauffmann et al. 1999) or the disk (disk model; e.g., Somerville & Primack 1999), or that half of the stars contribute to the bulge and the other half to the disk (disk-bulge model) of the more massive progenitor. Even though the case of the disk model is very unlikely and is not supported by *N*-body simulations, we included it as the opposite extreme to the bulge model, which demonstrates that the mass added by minor mergers is not negligible.

We find that the fraction of the Sp-E merger does not change significantly, while the fraction of Sp-Sp (E-E) mergers increases (decreases) from bulge to disk model (Fig. 3). This demonstrates that minor mergers play an important role between two major merging events of a galaxy. The stars and the gas contributed from the satellites will affect the morphology of elliptical galaxies and make them look more like lenticular galaxies.

It is interesting to investigate the fraction of present-day elliptical galaxies brighter than a given magnitude that experienced most recent major mergers of E-E, Sp-E, or Sp-Sp type. If bulge-dominated galaxies are defined as those with more than 60% of their mass in the bulge, we find that, independent of the fate of the satellite stars, more than 50% of the elliptical galaxies brighter than $M_B \sim -18$ have experienced major mergers that were not mergers between disk-dominated galaxies.

3. DISCUSSION AND CONCLUSIONS

We have analyzed the morphologies of progenitors of present-day elliptical galaxies based on their stellar mass content in the bulge and the disk, and we find that in contrast to the common assumption of disk-dominated progenitors, a large fraction of elliptical galaxies were formed by the merging of a bulge-dominated system with a disk galaxy or with another

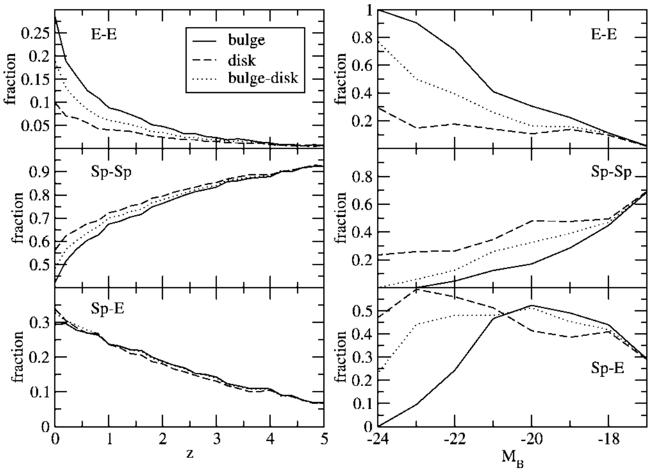

FIG. 3.—Same as Fig. 2, but assuming that galaxies with more than 60% of their mass in the bulge are called elliptical galaxies and adopting different fates for the stars of the satellites in minor mergers. We show models in which stars contribute to the bulge (*solid line*) or to the disk (*dashed line*) or in which half of the stars contribute to the disk and half to the bulge (*dotted line*).

bulge-dominated system. Kauffmann & Haehnelt (2000) find that the fraction of gas involved in the most recent major merger of present-day elliptical galaxies decreases with stellar mass. We find the same behavior and show that, in addition, the fraction of spheroidal and mixed mergers increases with luminosity, suggesting that massive elliptical galaxies mainly formed by nearly dissipationless mergers of elliptical galaxies (spheroidal mergers). Our results, combined with those of Milosavljević & Merritt (2001), provide an explanation for the core properties of elliptical galaxies as observed, e.g., by Gebhardt et al. (1996). Progenitors of massive elliptical galaxies should be bulge-dominated, with massive black holes and very little gas. Their merging leads naturally to flat cores in the remnant. In contrast, progenitors of low-mass elliptical galaxies are gas-rich, with small bulges and low-mass black holes, resulting in dissipative mergers and cuspy remnants. With these assumptions, it is possible to reproduce the relation between the mass deficit and the black hole mass observed by Milosavljević et al. (2002; S. Khochfar & A. Burkert 2003, in preparation). It is also interesting to note that Genzel et al. (2001) and Tacconi et al. (2002) find that ultraluminous infrared galaxies (ULIRGs) have effective radii and velocity dispersions similar to those of intermediate-mass disky elliptical galaxies with $-18.5 \geq M_B \geq -20.5$ (Sp-E region). QSOs, on the other hand, have effective radii and velocity dispersions that are similar to giant boxy elliptical galaxies (E-E region). This suggests that ULIRGs should be formed in Sp-E mergers, whereas QSOs are formed almost dissipationless through E-E mergers.

As noted by F. Schweizer in Kennicutt et al. (1998), 25%–50% of all elliptical galaxies show the presence of kinematically decoupled nuclear disks. Such disks will be disrupted in dissipationless mergers (E-E). Figure 1 shows that in the range in which most of the elliptical galaxies are observed ($M_B > -22$), the formation process is dominated by Sp-E and Sp-Sp mergers. Franx & Illingworth (1988) suggested that kinematically decoupled cores could originate from an elliptical galaxy merging with a gas-rich spiral galaxy (Sp-E). Adopting this hypothesis, it turns out that the fraction of Sp-E and Sp-Sp mergers is sufficient to provide up to 50% of decoupled cores in the remnants.

We find that many bulge-dominated progenitors experienced minor mergers in between two major merger events. The morphology of these objects is somewhat ambiguous and may depend on several parameters, like the impact parameter of the infalling satellites. However, it is clear that these galaxies will look like lenticular galaxies rather than classical spiral galaxies. If lenticular galaxies make up a large fraction of progenitors of present-day elliptical galaxies with $M_B \lesssim -21$, numerical simulations of the formation of giant elliptical galaxies should start with progenitors that were disturbed by minor mergers and should not use relaxed spiral galaxies (e.g., Burkert & Naab 2003).

Independent of the fate of satellite stars in minor mergers, more than 50% of present-day elliptical galaxies brighter than $M_B \sim -18$ in clusters had a most recent major merger that was not a merger between two classical spiral galaxies. Despite all the successes of the simulations of merging spiral galaxies in explaining elliptical galaxies, our results indicate that only low-mass elliptical galaxies are represented by such simulations. Previous simulations of Sp-E and E-E mergers were preformed in the context of groups (Barnes 1989; Weil & Hernquist 1996) but were not addressed with isolated galaxies in high-resolution simulations. Therefore, more simulations of Sp-E (e.g., Naab & Burkert 2000) and E-E mergers are required to address the question of the formation of elliptical galaxies via adequate merging.

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