ABSTRACT

Using semi-analytical models of galaxy formation, the origin of boxy and disky elliptical galaxies is investigated. We find that the simple scenario, motivated by N-body simulations, in which the isophotal shape is only dependent on the mass ratio of the last major merger, is not able to reproduce the observation that the fraction of boxy and disky ellipticals depends on galaxy luminosity. The observations can however be reproduced with the following reasonable assumptions: (i) equal-mass mergers lead to boxy ellipticals and unequal-mass mergers produce disky ellipticals (as motivated by N-body simulations) (ii) major mergers between bulge-dominated galaxies result always in boxy ellipticals, independent of the mass ratio, (iii) merger remnants that subsequently accrete gas leading to a secondary stellar disk with more than 20% the total stellar fraction are always disky. This scenario indicates that the isophotal shapes of merger remnants are sensitive to the morphology of their progenitors and subsequent gas infall. Boxy and disky ellipticals can be divided into two subclasses, depending on their formation history. Boxy ellipticals are either formed by equal mass mergers of disk galaxies or by major mergers of early-type galaxies. We find that disky ellipticals are indicators of unequal-mass mergers or late gas infall. Disky ellipticals with high luminosities are preferentially 1-component systems that result from unequal mass mergers whereas low-luminosity disky ellipticals are more likely to harbour secondary disk components. In addition, the fraction of disky ellipticals with secular disk components should increase in regions with higher galaxy densities. Taking into account the conversion of cuspy cores into flat low-density cores by black hole merging we find that disky ellipticals should contain central density cusps whereas boxy ellipticals should in general be characterised by flat cores. Only rare low-luminosity boxy ellipticals, resulting from equal-mass mergers of disk galaxies could have power-law cores.

Key words: dark matter – galaxies: ellipticals – galaxies: formation
formation histories. Interestingly, most of the massive ellipticals are boxy, while 2/3rd of the lower-mass ellipticals are disky (Bender, Burstein, & Faber 1992).

In order to understand the origin of boxy and disky ellipticals within the framework of the major merger scenario, numerical merger remnants of dissipationless mergers have been analysed in detail e.g. by Hernquist (1993), Heyl et al (1994), Lima-Neto & Combes (1995), Naab et al (1999) and Bendo & Barnes (2000). In addition the role of gaseous dissipation on the isophotal shape of remnants has been investigated in various studies e.g. by Barnes & Hernquist (1993), Bekki & Shioya (1997) and Springel (2000). These studies find in agreement with each other that gaseous dissipation leads to enhanced diskyness in the remnant. Bekki & Shioya (1997) simulated a number of mergers between bulgeless disk galaxies with purely gaseous disks which depending on the rapidity of star formation tend to be more likely disky (boxy) for weak (strong) star formation efficiency. This result can be understood in terms of gas that has lost large parts of its angular momentum and settles down in the centre of the remnant, increasing the potential well and thereby destabilising box-orbits passing the central region (Barnes & Hernquist 1996). The amount of gas able to settle down into the centre is strongly correlated with the efficiency by which gas is transformed into stars which explains the trend observed in the simulations. However, Springel (2000) demonstrated that this effect is much weaker in the presence of a stellar bulge component. Kauffmann & Haehnelt (2000) and Khochfar & Burkert (2003) showed that the role of dissipation in the formation of massive spheroids is weaker compared to its role in the formation of low mass spheroids. Furthermore massive spheroids tend to form mainly by mergers of progenitors already consisting of massive bulge components (Khochfar & Burkert 2003). In the following, we will compare our results to the giant and parts of the intermediate elliptical sample with absolute B-band magnitude $M_B \leq -18.5$ of Bender, Burstein, & Faber (1992) allowing us to neglect the influence of dissipation during the merger process on the isophotal shape.

Recently, Naab & Burkert 2003 (for a summary see also Burkert & Naab 2003) completed a large survey of dissipationless merger simulations of disk galaxies, adopting a statistically unbiased sample of orbital initial conditions with mass ratios of 1:1 to 4:1. They showed that unequal mass 3:1 to 4:1 mergers lead to fast rotating disky ellipticals, in excellent agreement with observations. In contrast, slowly rotating, pressure supported ellipticals formed in equal mass 1:1 to 2:1 mergers of disk galaxies while 2:1 to 3:1 mergers lead to remnants with mixed isophotal shapes.

In this paper we investigate whether the scenario of disky and boxy elliptical formation based on mass ratios in major mergers is in agreement with the observed distribution of ellipticals with different isophotal shape. Using semi-analytical simulations we predict the ratio of boxy and disky ellipticals as a function of their luminosity. In section 2 & 3 we introduce the semi-analytic approach we use and the way in which we assign isophotes to modelled ellipticals. Section 4 compares our model predictions with observations and in section 5 we introduce two new sub-classes of elliptical galaxies followed by a concluding section.

2 FORMATION OF ELLIPTICALS

We follow the formation and evolution of elliptical galaxies in the context of semi-analytical modelling of galaxy formation. The history of dark matter halos is traced using the merger tree proposed by Somerville & Kolatt (1999) and the baryonic physics is treated as described e.g. in Springel et al (2001). The dark matter merger trees are resolved down to a minimum mass of $M_{min} = 10^{10} M_\odot$ and calculated for a set of different present day dark halo masses ($M_h = 10^{13}, 10^{14}, 10^{15} M_\odot$). Larger halo masses correspond to more dense environments, as e.g. $M_h = 10^{15} M_\odot$ and $M_h = 10^{13} M_\odot$ corresponds to a present day cluster and field environment, respectively. The resolution limit we adopt does not influence our results as we will show in the next section. We assume a ΛCDM model with cosmological parameters $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = 0.7$, $\Omega_m/\Omega_b = 0.16$ and $\sigma_8 = 0.9$.

The galaxy formation paradigm inherent to semi-analytic models assumes that the first galaxies to form are bulge less disk galaxies (see however D’Onghia & Burkert 2001) which form stars in centrifugally supported disks of cooled gas (e.g. White & Frenk 1991). Subsequently spheroids, elliptical galaxies and bulges, are formed in major mergers with mass ratios $M_{gal,1}/M_{gal,2} \leq 3.5$ ($M_{gal,1} \geq M_{gal,2}$) of galaxies as proposed by Toomre & Toomre (1972) (e.g. Kauffmann et al 1999, Springel et al 2001). We adopt a scheme identical to the one used in e.g. Springel et al (2001) in which each galaxy in the semi-analytical simulation consists of two stellar components, a disk and a bulge component.

2.1 Disk Component

The disk component grows through hot gas that radiatively cools from the halo region and settles into the equatorial plane of a galaxy where it is transformed into a secular stellar disk. The cooling rate is calculated using the prescription described in Springel et al (2001). Additionally we allow disks to grow by accretion of the cold gas in the disks of satellite galaxies in minor mergers. We neglect any further possible ways of growing disks and comment on that in the next section.

2.2 Bulge Component

The bulge component grows through major mergers of galaxies. We calculate the timescale for galaxies to merge using the approach in Kauffmann et al (1999) with the modification of using the approximation of the Coulomb logarithm as proposed in Springel et al (2001). Mergers disrupt the progenitor disks as seen in various numerical simulations (e.g. Barnes & Hernquist 1992, Burkert & Naab 2003 and reference therein) and relax to a spheroidal distribution. During the merger any cold gas in the disk of the progenitor galaxies is assumed to be funnelled into the centre of the remnant where it ignites a star burst which transforms all of the cold gas into stars contributing to the spheroidal component (e.g. Kauffmann et al 1999, Springel et al 2001, and reference therein). The second assumption is certainly a simplification of what might happen since we neglect that not all of the cold gas is funnelled to the centre but some fraction of it can e.g. settle down in an extended disk which continues
growing inside out by fresh supply of gas from tidal tails (e.g. Barnes & Hernquist 1991; Mihos & Hernquist 1996; Barnes 2001, 2002. However, 2003). Another simplifying assumption is that we neglect an underestimate of the secondary disk components in our approach. The prescription for the faith of the cold gas we adopt results in an overestimate of the spheroid masses and an underestimate of the secondary disk components in our model, which is not very significant for massive ellipticals since they are mainly formed in relatively weak dissipative mergers (Kauffmann & Haehnelt 2000; Krichfar & Burkert 2003). Another simplifying assumption is that we neglect the feeding of super massive black holes in the centre of the remnant or feedback effects on the gas from the central source. However, Haehnelt & Kauffmann (2001) estimate that a cold gas mass fraction of less than 1% accreted onto the black hole is sufficient to recover the $M_* - \sigma$ relation and we therefore neglect this effect. Furthermore we assume, that the bulge components of galaxies grow in minor mergers by the stars of infalling satellites.

2.3 Morphological Classification

The above description for the growth of different stellar components allows for morphological transitions of individual galaxies. All galaxies start off as bulgeless disk galaxies which later transform into elliptical galaxies in major mergers, and then possibly grow new secondary disks through the combined effect of cooling of hot gas from halo regions and cold gas accretion in minor mergers. In this way, provided that enough cold gas is accreted, the ellipticals could also become bulges of early-type spirals until the next major merger which destroys the disk again and creates a new elliptical galaxy when the process of disk growing starts again. The knowledge of the bulge and disk components allows for a morphological classification of modelled present day galaxies using the correlation between the Hubble type $T$ and the $B$-band bulge-to-disk ratio of galaxies presented in Simien & de Vaucouleurs (1986). Elliptical galaxies are classified by $T < -2.5$ and have $\Delta M = M_B,\text{bulge} - M_B,\text{tot} \leq 0.55$. Our definition of morphology bares some danger with respect to lenticular galaxies. Generally semi-analytic models assume $-2.5 < T < 0.92$ for S0 galaxies, identifying them as a transition type between ellipticals and spirals, in the process of regrowing a secondary disk after a major merger (Kauffmann et al. 1999). Alternative formation mechanisms e.g. involve either the unequal mass mergers of two spiral galaxies (Eke 1995; Barnes 1996; Bendo & Barnes 2001) in which the larger progenitor’s disk basically survives the merger, or the growing of a secondary disk by material from tidal tails (Mihos 2004). As a consequence, our population of ellipticals formed in mergers should be polluted with S0 galaxies. At this stage, a clear separation between modelled disky ellipticals and S0 galaxies is not possible and is hindered by observational ambiguities due to projection effects. We therefore do not distinguish between disky ellipticals and S0 galaxies for $T < -2.5$.

3 ASSIGNING ISOPHOTES

Following the work of Barnes (1998), Naab et al. (1999) and Naab & Burkert (2003) we assign isophotes to elliptical galaxies according to the mass ratio of their last major merger. Last major mergers with mass ratio $1 < M_{\text{gal,1}}/M_{\text{gal,2}} < 2$ and $2 < M_{\text{gal,1}}/M_{\text{gal,2}} < 3.5$ (for $M_{\text{gal,1}} > M_{\text{gal,2}}$) lead to boxy and disky ellipticals, respectively.

Fig. 1 shows the ratio of boxy to disky elliptical galaxies depending on their present day $B$-band magnitude, assuming a final dark halo mass of $10^{13} M_\odot$. The ratio is almost constant with $N_{\text{boxy}}/N_{\text{disky}} \sim 0.5$ over the presented magnitude range. This result is a consequence of the self-similar build up of elliptical galaxies by major mergers on all mass scales. We mentioned above that we follow dark matter histories back until progenitor halos drop below $M_{\text{min}} = 10^{10} M_\odot$. The different symbols in the upper panel Fig. 1 show the results of a resolution study of this minimum mass. By increasing the resolution (i.e. decreasing $M_{\text{min}}$) we also increase the number of resolved small mass satellite galaxies in the overall galaxy population. As shown, the results do not change which is due to small mass satellite galaxies not significantly taking part in the last major major mergers at these luminosity scales. In the following we will use a mass resolution of $M_{\text{min}} = 10^{10} M_\odot$, which is a good compromise between efficiency and accuracy.

It is well known that, observationally, the fraction of elliptical galaxies increases with the galaxy density of the environment (e.g. Dressler 1980, a trend also seen in simulations of galaxy formation (e.g. Springel et al. 2001), and reference therein), which is attributed to the increased merger rate. The fraction of major mergers and its redshift evolution are very sensitive to environmental effects (Krichfar & Burkert 2001). However, one is not expecting to find the relative fraction of major mergers for a given mass ratio to change with the environment. The lower panel of Fig. 1 shows the de-
pendence of the ratio of boxy-to-disky ellipticals on the final dark halo mass which corresponds to different environments. Large final masses represent higher density environments, like clusters, low-mass represent a field environment. There is no significant environmental dependency, suggesting that the mix of boxy to disky ellipticals is universal.

4 COMPARISON WITH OBSERVATIONS

The next step is to compare the model predictions to observations by Bender, Burstein, & Faber (1992) who presented a first systematic study of the correlation of the isophotal shape with other physical properties of ellipticals. Naab et al. (1999); Naab & Burkert (2003) used the same reduction routines as Bender, Burstein, & Faber (1992) in their merging simulations to derive the isophotal properties of their remnants. It is therefore safe to assume that we do not introduce any ambiguities in our definition of boxy and disky ellipticals by adopting their predicted dependence of isophotal shape on the mass ratio of the merger.

4.1 A First Test

The data of Bender, Burstein, & Faber (1992) shows a trend that the most massive ellipticals are mainly boxy, while the least massive ones are mainly disky. We compare this data with the model predictions in Fig. 2. This comparison shows a clear failure of the theoretical model as it does not reproduce the trend seen in the observations. This is a generic feature of the cold dark matter paradigm. Any property of a galaxy which depends on the mass ratio of the last major merger will be scale free.

4.2 Modifying the Model

The numerical simulations which motivated the previous analysis still leave space for further interpretation. It is e.g. not yet fully understood what influence gas will have on the structure of the merger remnants. Galaxy mergers in numerical simulations usually start with relaxed spiral galaxies even though galaxy formation models predict that mergers between elliptical galaxies or elliptical and spiral galaxies occur too. In the following sections we therefore study the possible effect of mergers between different galaxy morphologies and gas infall on the ratio of boxy to disky ellipticals.

4.2.1 Progenitor Galaxies

Recent semi-analytic simulations of galaxy formation by Khochfar & Burkert (2003) showed a remarkable correlation between the luminosity of elliptical galaxies and the morphology of their progenitor galaxies. The most luminous elliptical galaxies had preferentially experienced the last major mergers between two elliptical galaxies and not between two spiral galaxies. Only low luminous galaxies are formed by pure gas rich spiral mergers. Kormendy & Bender (1996) and Faber et al. (1997) argued along the same line that the most massive elliptical galaxies with boxy isophotes are most probably the outcome of a dissipationless merger, while less massive ellipticals with disky isophotes result from the merger of two gas rich galaxies, which leads to the formation of a secondary disk in the remnant.

The simulations analysed by Barnes (1998); Naab et al. (1999); Naab & Burkert (2003) used the same reduction routines as Governo et al. (1993), who showed that the remnant will have most likely boxy isophotes. In the following, we will assume that ellipticals having last major mergers between two bulge dominated galaxies ($M_{\text{bulge}} \geq 0.6M_{\text{tot}}$) will result in boxy remnants independent of the mass ratio. For all the other major mergers we adopt the original prescription.

Figure 3 shows the result of including this dependence on the progenitor morphologies for different environments. We now find indeed a correlation with luminosity, independent of environment. The most luminous elliptical galaxies are mainly boxy and the fraction of boxy ellipticals decreases with decreasing luminosity. This trend is an imprint of the high fraction of early-type mergers for luminous galaxies. Khochfar & Burkert (2003) found this fraction to be independent of environment which explains the results in Fig. 3. However, the gradient which we find is still not as strong as observed, although the observational uncertainties are large.

4.2.2 Disks in Ellipticals

After the last major merger, elliptical galaxies can continue to grow disks; one can identify three main processes of disk growth after major mergers. As noted above, gas in tidal tails can settle down into a disk after the spheroid has formed. We also noted above that we do not model this process and instead assume that the gas in the tidal tails is accreted to the centre of the remnant at the same time as the other present cold gas in the disks of the merging galaxies. The second and third process in growing a disk involve the cooling of hot gas from halo regions and the accretion of cold gas from satellite galaxies in minor mergers, respectively. In the following we are going to investigate the influence of the
last two processes mentioned above on the mix of ellipticals with different isophotal shapes. [Rix & Whitic 1991] find that some ellipticals show evidence for embedded stellar disks with up to 30% of the total baryonic mass. It is likely that ellipticals with disks of that order will be disky, independent of the details of the last major merger. Figure 3 shows the results if we include this effect in our model. Here we assume that an elliptical will be disky if a stellar disk component is present, generated by the combined effects of cooling and satellite accretion, which contains more than 20% of the total baryonic mass. This value is a lower limit based on estimates derived from artificially adding an additional stellar disk to a merger remnant and deriving the isophotal shape of it (Naab, private communication). We ran some tests with different values for the lower limit when a elliptical becomes disky, finding that for a value of 30% the fraction of boxy to disky elliptical did not change. For a value lower than 20% the fraction of boxy to disky elliptical galaxies decreases, especially for low-luminosity systems which on average have their last major merger is included. The mass resolution in all runs is $M_{\text{min}} = 10^{9} \, M_{\odot}$.

Figure 3. The ratio of boxy to disky ellipticals as function of magnitudes as predicted by the simulations. Filled circles show the observational data of Bender, Burstein, & Faber (1992), the open symbols show the theoretical predictions for different galaxy environments as presented also in Fig. 1 (lower panel). The dependence on the morphology of the progenitor galaxies in the last major merger is included. The mass resolution in all runs is $M_{\text{min}} = 10^{9} \, M_{\odot}$.

Figure 4. Ratio of boxy to disky ellipticals for different magnitudes found in the simulation. Filled circles show the data of Bender, Burstein, & Faber (1992) and open symbols the results for the environments presented in Fig. 1 (lower panel) including the dependence of the isophotal shape on the morphology of the progenitor galaxies in the last major merger of ellipticals and the formation of a secondary disk by gas infall into the remnant. The mass resolution in all runs is $M_{\text{min}} = 10^{9} \, M_{\odot}$.

5 ISOPHOTAL SUB-CLASSES

The results of the last section suggest that boxy as well as disky isophotes have two distinct origins in ellipticals. Each formation scenario is expected to leave signatures in the structural properties of the remnant. Observations of surface brightness profiles also suggest a dichotomy [Lauer et al. 1995; Gebhardt et al. 1996; Faber et al. 1997]. Similar to the separation into boxy and disky isophotes, ellipticals can be classified into core and power-law galaxies, depending on the inner slope of the surface brightness profile. High luminous elliptical galaxies show shallow inner profiles (core galaxies) and low luminous ellipticals show steep inner slopes (power-law galaxies). It is still a matter of debate whether this dichotomy is real or artificial as argued by Graham & Guzmán 2003 who find a continuous linear relation between the Sersic index $n$ and the absolute magnitude of the elliptical galaxies. For our present analyses we will assume that a dichotomy exist. [Rest et al. 2001] analysed the correlation between isophotal shape and the shape of the central surface brightness profile. They showed that most of the boxy ellipticals and disky ellipticals are classified as core and power-law galaxies, respectively. Note that not all of the boxy ellipticals have a core and not all of the disky ellipticals are power-law galaxies, suggesting that each isophotal class might be subdivided into two subclasses, depending on their core properties. In the following we investigate the origin of these subclasses and test whether our model can account for the observation by [Rest et al. 2001].

5.1 Boxy Ellipticals: flat-density cores versus power-law cores

Our model predicts that boxy ellipticals form by two mechanisms, equal mass mergers of two galaxies and major mergers...
bour super-massive black holes (SMBH) which follow a $M$-dominated galaxies. It is widely accepted that spheroids have "" 

resolution in all runs is $M_{\text{min}} = 10^{10} \, M_\odot$.

$(M_{\text{gal},1}/M_{\text{gal},2} < 3.5, \ M_{\text{gal},1} \geq M_{\text{gal},2})$ of two spheroidally dominated galaxies. It is widely accepted that spheroids harbour super-massive black holes (SMBH) which follow a $M_\bullet - \sigma$ relation [Ferrarese & Merritt 2000; Gebhardt et al. 2000]. [Milosavljević & Merritt 2001] investigated the merger of two galaxies harbouring SMBHs and found that the remnant will have a light profile showing a core in the centre. We therefore assume that the major mergers between spheroidal dominated ellipticals will lead to the formation of core galaxies with boxy isophotes. Equal mass mergers between disk dominated galaxies harbouring no SMBH or SMBH with small masses will not lead to the creation of a core due to binary black hole merging. In fact, gas infall into the centre during the merger and subsequent star formation are likely to regenerate cusps. We therefore assume that these mergers generate power-law galaxies.

Fig. 5 shows the ratio of power-law to core boxy elliptical galaxies at each magnitude for different environments. We find no significant environmental dependence. The number of core galaxies increases from about 0.1 to 3 times the number of power-law galaxies from low to high luminosities. [Rest et al. 2001] use three main profile classes: core, power-law and intermediate. Following the original work of [Faber et al. 1997] we classify intermediate galaxies as core galaxies and compare the data of [Rest et al. 2001] with our results in Fig. 5. We find that the agreement between the simulations and the observations in the overlapping luminosity range is very good. Unfortunately, due to the limited data, it is not possible to compare the observational data with the simulations over a wider range of luminosities.

5.2 Disky ellipticals: central properties, 1-component versus 2-component galaxies

The observations of [Rest et al. 2001] show that it is very unlikely to find disky ellipticals which are also core galaxies. In fact they find only 1 out of 21. Our simple model does not allow for disky ellipticals which have a core. The reasoning behind this is that we assume core galaxies form by the mergers of two bulge dominated galaxies harbouring SMBH. This results in the formation of boxy ellipticals. In principle, it is possible to generate disky core-ellipticals; consider two disk galaxies with significant bulge components $M_{\text{bulge}} < 0.5 M_{\text{tot, baryons}}$. The bulges will harbour SMBH. Unequal mass mergers between them would result in disky ellipticals. Cores might still form when the massive black holes spiral into the centre. At the moment, due to the lack of detailed simulations it is not clear whether black hole merging in this case would be efficient enough to generate cores. In addition, since the combined mass of the progenitor SMBHs is smaller than that expected for the SMBH in the remnant according to the $M_\bullet - \sigma$ relation, the black holes must grow significantly in mass by gas accretion in contrast to the case of two bulge dominated merging galaxies. Gas infall into the central region could trigger central star formation which might change the core density distribution, leading again to cuspy profiles. Given this complexity, we do not try to model the fraction of disky core galaxies, which according to the observations is small anyway.

The fraction of disky elliptical galaxies with massive secular disks formed after the last major merger is very sensitive to both the environment and the amount of residual star formation in elliptical galaxies. Recent results from the GALEX mission indicate that there is indeed residual star formation occurring in elliptical galaxies (S. K. Yi, private communication). It is not yet clear where exactly this star formation occurs even though there are indications that it is in a disk-like substructure. Figure 6 shows the ratio of disky ellipticals formed by unequal mass mergers between disk galaxies (1-component disky) to disky ellipticals which have grown secular massive disks after their last major merger by gas accretion (2-component-disky). Most disky ellipticals are predicted to be 1-component systems that resulted from unequal-mass mergers. We find a larger fraction of 2-component disky ellipticals in high density environments.
rather than in low density environments. In addition the fraction of 2-component disky ellipticals decreases toward higher luminosities. In high density environments, at luminosities of $M_B \sim -18$, the fraction of 2-component disky ellipticals is comparable to the fraction of 1-component disky ellipticals.

6 DISCUSSION AND CONCLUSION

We used semi-analytical simulations to investigate the formation of disky and boxy ellipticals. A comparison with observations shows that the isophotal shape cannot only depend on the mass ratio of the last major merger. In this case, galaxy properties which depend only on the mass ratio of the last major merger should be scale free. The fraction of disky-to-boxy ellipticals, however, shows a strong mass dependence. To break the mass degeneracy, we propose that the isophotal shape should, in addition to the mass ratio, depend also on the morphology of the progenitors of the last major merger. Our model can reproduce well the observed trend of the ratio of ellipticals with boxy and disky isophotes with luminosity within the observational uncertainties due to the low number statistics. In particular, the inclusion of the contribution of an additional disk component results in a reduction of the fraction of boxy ellipticals mainly at low luminosities, while early-type mergers increase the fraction of boxy types at high luminosities. The model predicts a dependence on the environment once disk formation by gas accretion is taken into account. Galaxy assembly by major mergers occurs in high density environments at earlier times allowing secular disks to grow for longer times and hence become a more important component in terms of total baryonic mass fraction.

We find two populations of disky ellipticals, those formed by unequal mass mergers, called 1-component disky, and those who grew new disks and were originally boxy or 1-component disky ellipticals, called 2-component disky. The fraction of 2-component disky ellipticals is a strong function of the luminosity and environment. As massive ellipticals form late, they do not have time to grow secular disks. Disky massive ellipticals therefore are mainly 1-component systems, which result from unequal-mass mergers. The disks in 2-component disky ellipticals will be on average younger than their bulge populations. We predict that such disks will be mainly found in cluster environments where, at luminosities around $M_B \sim -18$, half of the disky ellipticals should be 2-component systems. If these disks would continue to grow, they would transform the elliptical into a Sa or Sb galaxy. It is not clear whether the galaxy at an intermediate stage will look like an S0 galaxy or whether S0s are sometimes 2-component ellipticals seen under certain projections. Observations analysing the stellar orbital distribution in disky ellipticals will be able to distinguish between the two populations of disky ellipticals.

We predict also two populations of boxy elliptical galaxies, power-law-boxy, made by equal mass mergers of disk galaxies, and core-boxy, made by any major merger but between two elliptical galaxies. We find that the fraction of core-to-power-law galaxies increases toward higher luminosities because of a higher fraction of mergers between bulge dominated galaxies. However, we do not find an environmental dependence due to the self-similar build-up through mergers. The observations of [Rest et al. (2001)] agree very well with our predictions. A larger observational study will be required to test the relation which we find for a larger magnitude range.

Bender, Burstein, & Faber (1992) argued that ellipticals can be divided in two main categories, boxy and disky ellipticals. Our study shows that to recover observational trends we need to make assumptions on the formation process of ellipticals which introduce additional sub-classes. The boxy and disky sub-classes have different origins which are closely related to the hierarchical build-up of structure and local gas physics. The two boxy classes differ because of the properties of their progenitors which are again dependent on the previous merging history. The two disky classes differ because of the baryonic gas physics, namely the build up of a disk by gas accretion after the last major merger. By comparing the predicted fractions of boxy and disky sub-classes with observations it will be possible in the future to clarify the importance of gas physics coupled to star formation and the influence of the global dark matter merging history on the origin of early-type galaxy morphologies.

The authors would like to thank Ralf Bender, Thorsten Naab, Sukyoung Yi and the referee for useful comments. SK acknowledges support by PPARC Theoretical Cosmology Rolling Grant and by the STScI where part of this work has been done. AB acknowledges the support of the Aspen Center of Physics where part of this work was done.

REFERENCES

Barnes, J. E. 1988, ApJ, 331, 699
Barnes, J. 1996, IAU Symp. 171: New Light on Galaxy Evolution, 171, 191
Barnes, J. E. 1998, Saas-Fee Advanced Course 26: Galaxies: Interactions and Induced Star Formation, 275
Barnes, J. E. 2001, Astronomical Society of the Pacific Conference Series, 240, 135
Barnes, J. E. 2002, MNRAS, 333, 481
Barnes, J. E., & Hernquist, L. E. 1991, ApJL, 370, L65
Barnes, J. E. & Hernquist, L. 1992, Ann. Rev. of Astronomy and Astrophysics, 30, 705
Barnes, J. E., & Hernquist, L. 1996, ApJ, 471, 115
Bekki, K. 1998, ApJL, 502, L133
Bekki, K., & Shioya, Y. 1997, ApJL, 478, L17
Bender, R. 1998, A&A, 193, L7
Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Bendo, G. J. & Barnes, J. E. 2000, MNRAS, 316, 315
Burkert, A & Naab, T. 2003, in Galaxies and Chaos, eds. G. Contopoulos, N. Voglis, Lecture Notes in Physics, 626, p327
Cimatti, A., et al. 2004, NATURE, 430, 184-187
D’Onghia, E. & Burkert, A. 2004, astro-ph/0402504
Dressler, A. 1980, ApJ, 236, 351
Faber, S. M., et al. 1997, AJ, 114, 1771
Ferrarese, L. & Merritt, D. 2000, ApJL, 539, L9
Gebhardt, K., et al. 1996, AJ, 112, 105
Gebhardt, K., et al. 2000, ApJL, 539, L13
