Are disk galaxies the progenitors of giant ellipticals?

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ABSTRACT

A popular formation scenario for giant elliptical galaxies proposes that they might have formed from binary mergers of disk galaxies. Difficulties with the scenario that emerged from earlier studies included providing the necessary stellar mass and metallicity, maintaining the tight color-magnitude relation and avoiding phase space limits. In this paper we revisit the issue and put constraints on the binary disc merger scenario based on the stellar populations of disc galaxies. We draw the following conclusions: Low redshift collisionless or gaseous mergers of present day Milky Way like disc galaxies do not form present day elliptical galaxies. Binary mergers of the progenitors of present day disc galaxies can have evolved into intermediate mass elliptical galaxies ($M < M_\ast$) if they have merged earlier than $\approx 4$ Gyrs ago. But more massive giant ellipticals in general can not have formed from binary mergers of the progenitors of present day disc galaxies. They must be made from either multiple mergers or binary mergers of spirals at early times whose descendents no longer exist. A major reason for these conclusions is that the mass in metals of typical disk galaxy is approximately a factor of $4-8$ smaller than the mass in metals of a typical early-type galaxy and this ratio grows to larger values with increasing redshift.

Key words: methods: analytical – methods: N-body simulations – galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: evolution – galaxies: fundamental parameters

1 INTRODUCTION

How did elliptical galaxies form? After more than a decade of high resolution observations from space and new powerful numerical simulations, additional insight has been gained but also new and old questions have been raised. Red bulge-dominated galaxies contain at least half of the stellar mass of the universe (Fukugita et al. 1998; Hogg et al. 2002) and adding bulges of spiral galaxies the fraction might be as high as $3/4$ (Bell et al. 2003). Therefore a consistent theory for elliptical galaxy formation is of fundamental importance but it is still unavailable. Independent of the cosmological context, the luminous parts of massive galaxies must have formed by collecting baryonic material under the influence of gravity. So, in the most general sense ‘mergers’ of some type are of course necessarily the precursors of present day elliptical systems. The questions are when and how they have formed. There are a variety of possibilities concerning how this could have happened. Depending on whether the infalling material has already collapsed and formed stars the galaxy could either accrete stars or accrete gas which is then turned into stars thereafter within the galaxy. In addition, the distribution of sizes and gas fractions of the accreted material might vary with time. The choice of these parameters is not completely arbitrary and a detailed theory of elliptical galaxy formation must be constrained by comparison with the properties of observed elliptical galaxies and of the progenitor components.

It has been known for decades that giant elliptical galaxies are a homogeneous family of galaxies with old stellar populations (e.g. Faber & Jackson 1976; Kormendy & Djorgovski 1989; Thomas et al. 2005). Therefore it has been suggested that they all have formed in situ at early times (Brinchmann & Ellis 2000). Without, at this earlier time, detailed knowledge of the, currently popular, hierarchical cosmological models, the ‘monolithic collapse’ scenario was designed to explain the early formation of ellipticals motivated by the Eggen et al. (1962) proposal that the old spheroidal component of the Milky Way formed during a short period of quasi-radial collapse of gas some $10^{10}$ Gyrs ago and, in most of their properties, the spheroidal bulges of spiral and S0 galaxies are indistinguishable from ellipticals of the same luminosities.

In that sense, an elliptical/spheroidal galaxy would have
formed very early, as soon as a finite sufficiently over-dense region of gas and dark matter decoupled from the expansion of the universe and collapsed. If, during the proto-galactic collapse phase, star formation was very efficient, a coeval spheroidal stellar system could have formed before the gas could have dissipated its kinetic and potential energy and would have settled into the equatorial plane, thus avoiding the formation of a disk galaxy (Partridge & Peebles 1967; Larson 1969, 1974; Searle et al. 1973). Depending on the amount of 'turbulent viscosity' and the angular momentum of the infalling gas, detailed properties like isophotal shapes, rotation, age and metallicity gradients and even the formation of disk-like substructures in elliptical galaxies have been computed decades ago (Larson 1975). The 'turbulent viscosity' was created by large inhomogeneities and random motions, eventually caused by independently moving gas clouds. Recent high resolution numerical simulations, using modern cosmological models, indicate that indeed there was a phase of evolution of this type (Naab et al. 2007) during which a small (\(\sim 1-2kpc\)), concentrated and massive system was formed rapidly at high redshifts (2 \(\leq z \leq 4\)).

At about the same time Toomre & Toomre (1972); Toomre (1974, 1977) investigated the tidal interactions during encounters of spiral galaxies and proposed that disk galaxies might eventually merge and form elliptical galaxies. This proposal became particularly attractive with the advent of hierarchical cosmological theories (White & Rees 1978) in which mergers play the dominant role during the formation and/or evolution of every dark matter halo and almost every galaxy at some time in its life. In this 'merger scenario' massive elliptical galaxies could have formed from the gravitational interaction of already existing massive galaxies that were not of early type.

2 THE DISK MERGER HYPOTHESIS

2.1 Collisionless disc mergers

In the early 80's the first fully self consistent simulations of mergers of stellar disk galaxies were performed (Gerhard 1981; Negroponte & White 1983). Using effective tree algorithms (Barnes & Hut 1986; Hernquist 1987; Barnes & Hut 1989) and more powerful general purpose and special purpose computers a whole industry of simulations of merging disk galaxies was created that was designed to answer the question of whether they form systems that resemble present day elliptical galaxies (Barnes 1988, 1990; Barnes & Hernquist 1992; Barnes 1992; Hernquist 1992; Naab & Burkert 2003; Jesseit et al. 2003; González-García & Balcells 2003; Naab & Trujillo 2006). The global properties of the remnants are in several respects consistent with observations of giant elliptical galaxies, e.g. equal mass remnants are triaxial, slowly rotating, anisotropic, have boxy or discy isophotes (Heyl et al. 1994; Naab & Burkert 2003). In addition, mergers of discs can result in the formation of kinematic subsystems like kinematically decoupled cores at the centers of ellipticals (Hernquist & Barnes 1991; Jesseit et al. 2006) as well as observed faint structures like shells, loops and ripples at large radii (Hernquist & Spergel 1992). Unequal mass mergers are more supported by rotation (Barnes 1998) and have discy isophotes (Naab & Burkert 2003). With respect to their intrinsic structure, all collisionless merger remnants are dominated by box orbits at their centers and tube orbits in the outer parts (Barnes 1998). The total fraction of tube orbits increases with the mass ratio of the mergers (Jesseit et al. 2004). The fraction of disc and box orbits correlates with the shape and kinematics of the systems and the mix of discy and boxy isophotal shapes for equal-mass remnants can be understood by the projected properties of tube orbits in triaxial potentials (Jesseit et al. 2004; Naab et al. 2006). Naab & Burkert (2003) and have argued, based on statistics of kinematic and photometric properties of equal- and unequal-mass mergers, that disc mergers (with bulges) can result in intermediate mass elliptical galaxies. But the objects so formed are not in agreement with the most massive, boxy and slowly rotating ellipticals. Khochfar & Burkert (2003) and Naab et al. (2006) indicate major binary early type mergers could be responsible for the properties of the most massive ellipticals.

Collisionless merger remnants in general have phase space densities and surface density profiles that resemble observed ellipticals only if bulges are added to the progenitor discs (see e.g. Carleberg 1984). The phase space densities of pure stellar disc mergers are too low (Hernquist et al. 1993; Naab & Trujillo 2006). In addition, intrinsic and isophotal shapes (Jesseit et al. 2005; Cox et al. 2006) as well as surface density profiles (Naab & Trujillo 2006) of pure disc mergers are not in agreement with elliptical galaxies. At this point, however, there remains the question of how bulges have formed in the first place.

The agreement of the kinematics of collisionless disc mergers and observed elliptical galaxies is only good to first order. At higher order there are disagreements with observed ellipticals. The line-of-sight velocity distributions (LOSVD) within the effective radius of merger remnants in general show small asymmetric deviations from Gaussian shape. They tend to have a steep trailing wing (Bendo & Barnes 2004; Naab & Burkert 2001; Naab et al. 2006), whereas most observed rotating ellipticals show a steep leading wing in their LOSVDs (Bender et al. 1994). Theoretically, axi-symmetric, rotating one-component systems show such a behaviour (Dehnen & Gerhard 1994). This would indicate that ellipticals are very simple one component systems that did not form by mergers, which is, however, unlikely (see e.g. Emel'yanov et al. 2004). An alternative explanation, based on photometric and kinematical observations, is that rotating ellipticals contain embedded large scale stellar discs (e.g. Bender 1988; Bender et al. 1999; Rix & White 1994; Scorza et al. 1998; Rix et al. 1998). A superposition of two distinct components, e.g. a hot spheroidal bulge and a rotationally supported cool disc, can also result in a steep leading wing of the LOSVD (Bender et al. 1994; Naab & Burkert 2001).

2.2 Disc mergers with gas

Evidently, disc galaxies do not only consist of stars but also an interstellar medium (ISM) in the form of gas. In the local universe for evolved disc galaxies typical gas fractions are 10 - 30 per cent of the total stellar mass (e.g. McGaugh & de Blok 1997). Within the hierarchical
paradigm the gas fraction is an increasing function with redshift. (see e.g. [Kochfar & Silk 2006]) Even if the overall gas fractions were relatively small, due to its dissipative nature gas can change the structure of merger remnants significantly (see e.g. [Kochfar & Silk 2006; Cotti et al. 2006]). It has been shown by [Barnes & Hernquist 1996] that gas accumulating at the center of merger remnants creates a steep cusp in the central potential well resulting in a more asymmetric central shape of the remnants [Barnes 1998]. At the same time the fraction of stars on box orbits is significantly reduced and tubes become the dominant orbit family [Barnes & Hernquist 1996]. The most reasonable explanation for this behaviour is that systems with steep cusps in their potential can not sustain a large population of box orbits [Gerhard & Binney 1985; Schwarzschild 1993; Merritt & Fridman 1996; Valluri & Merritt 1998; Barnes 1998; Naab et al. 2006]. One interesting consequence of the change of orbit populations is that the asymmetry of the LOSVD of the stars changes in a way that is consistent with observations making it a good dynamical tracer for the presence of gas during the merger (Naab et al. 2006).

Dissipational merging, including star formation, can also overcome stellar phase space constraints and therefore the a priori inclusion of a major spheroidal bulge component is not required, and it has been shown by [Robertson et al. 2006] that a progenitor gas fraction of 30 per cent results in remnants parameters in good agreement with the Fundamental Plane for elliptical galaxies. One interesting consequence of gas infall to the center and subsequent star formation is a break in the surface brightness profile with excess light at the center [Mihos & Hernquist 1994; Cox et al. 2006; an effect that is not seen in collisionless mergers Naab & Trujillo 2006]. For a long time this break in the surface density profiles has been considered not to be in agreement with the majority of elliptical galaxies. However, recent studies indicates that a break in the light profile might be a generic feature of low and intermediate mass ellipticals (Kormendy et al. 2007, submitted).

It has been known for some time [Hernquist 1984] that galaxy mergers can, by dynamical instabilities, drive large gas fractions to the center of the remnants probably causing a starburst and/or feeding a super-massive black hole [Mihos & Hernquist 1996; Barnes & Hernquist 1996; Bournaud et al. 2004, 2005; Springel et al. 2003]. Processes like this can be observed directly in nearby ultra-luminous infrared galaxies which are interacting disc galaxies at mass ratios in the range of 1:1 to 3:1 [Genzel et al. 1998, 2003; Dasvra et al. 2006]. Using a simple model for gas accretion onto a central super-massive black hole it has been argued, based on simulations of binary disc mergers, that gas inflow regulated by black hole feedback can naturally explain the observed present day relation between stellar velocity dispersion and black hole mass for elliptical galaxies and their evolution with redshift [Di Matteo et al. 2003; Robertson et al. 2006]. Extended models have also been used to understand the evolution of Quasars and stellar spheroids as a whole [Hopkins et al. 2003, 2004]. However, recent studies of dissipative mergers by [Naab et al. 2006], and, including star formation and feedback processes, by [Cox et al. 2006] confirm and strengthen the Naab & Burkert (2003) conclusion that binary disk mergers only are reasonable progenitors of intermediate mass giant ellipticals but not of the more massive ellipticals.

3 THE PROBLEM

Despite the success of the binary merger scenario for the formation of elliptical galaxies there remain fundamental problems comparing the stellar populations of present day elliptical and spiral galaxies. Several of the arguments presented in the following were outlined in primitive form by Ostriker (1984).

One aspect concerns the mass in metals of the two kinds of systems. We have estimated the typical mass of late-type and early-type galaxies by computing the mass above which half the total mass in galaxies of each type is contained assuming a lower limit of $10^9 M_\odot$. Using averages of the color and concentration selected mass functions of [Bell et al. 2003] we get $M_{\text{early}} = 7.5 \times 10^9 M_\odot$ and $M_{\text{late}} = 2.9 \times 10^9 M_\odot$. With typical metallicities for the respective populations of $z_{\text{early}} = 0.03$ and $z_{\text{late}} = 0.016$ [Nagamine et al. 2006] we get total masses in metals of $M_{\text{early}} = 2.3 \times 10^5 M_\odot$ and $M_{\text{late}} = 4.6 \times 10^5 M_\odot$. E.g. the mass in metals is $\approx 4.8$ times higher in typical ellipticals than in typical discs. Using an alternative approach using $L_*$ for early type and late type galaxies based on the SDSS data of [Nakamura et al. 2003] we obtain $M_{\text{early}} = 1.0 \times 10^{11} M_\odot$ and $M_{\text{late}} = 2.5 \times 10^9 M_\odot$ using $M/L_{\odot, \text{early}} = 3.19$ and $M/L_{\odot, \text{late}} = 1.18$ [Nagamine et al. 2006]. With the same typical metallicities we then get $M_{\ast \text{early}} = 3.1 \times 10^8 M_\odot$ and $M_{\ast \text{late}} = 4.1 \times 10^6 M_\odot$. This results in a $\approx 7.7$ times higher mass in metals of ellipticals.

Following the model for the evolution of the disc of our own galaxy, the Milky Way, presented in [Naab & Ostriker 2003] and extended here we find that the stellar component (disc and bulge) have a total mass of $5 \times 10^{10} M_\odot$ containing $\approx 8.4 \times 10^7 M_\odot$ solar masses in metals. The mean metallicity is in good agreement with typical estimates for the local disk galaxy population as whole, however, the total mass is slightly above the typical disc mass estimated before as the Milky Way is more massive than a typical disc galaxy. Still we can assume that the evolution with redshift is similar for all disks. With plausible assumptions for the evolution of the star formation rate the mass in metals for one disk galaxy was $\approx 50$ percent smaller at $z=1$ and $\approx 80$ percent smaller at $z=2$. Under the simplified assumption that early-type galaxies evolve passively since $z=2$ the progenitors of a typical present day disc have about 9-15 times less metals at $z=1$ and about 20-35 times less at $z=2$. Simply put the mass in metals of two typical spirals is significantly less than in typical ellipticals. And the problem becomes worse as one considers mergers at $z=1$ or even $z=2$. Clearly this problem is most severe for massive ellipticals.

Another aspect concerns the ages of the stellar populations. There is strong observational evidence that old, massive, red and metal rich proto-ellipticals are already in place at $z = 2 - 3$ and that present day early-type galaxies formed most of their stars well before a redshift $z = 1$ [Searle et al. 1978; van Dokkum & Franx 1996; Brinchmann & Ellis 2000; van Dokkum et al. 1993; Bender et al. 1998; Treu et al. 2003; van der Wel et al. 2003; van Dokkum et al. 2006; Kriek et al. 2006]. This sce-
nario would point towards a monolithic collapse picture. In general, elliptical galaxies are red and the formation of their stars was complete 8-10 Gyrs ago whereas disk galaxies in general are blue and have much younger stellar populations with e.g. mean ages of 5 Gyrs for the Milky Way (Robin et al. 2003). In combination with the fact that disc galaxies are less massive and smaller than massive elliptical galaxies it can be excluded that all elliptical galaxies could have formed from binary mergers of present day spiral galaxies. Of course elliptical galaxies might have formed from the progenitors of present day disc galaxies. But observations of the size and mass evolution of disc galaxies (Barden et al. 2005; Trujillo & Pohlen 2003; Trujillo et al. 2006) as well as a plethora of theoretical models (Chiappini et al. 1997; Mao et al. 1998; Prantzos & Silk 1998;Boissier & Prantzos 2001; Naab & Ostriker 2006) indicate that spiral galaxies in the past were in general smaller and less massive than today. As disk merger remnants typically have similar projected sizes and not more than two times the progenitor mass in the spheroidal component (Naab & Trujillo 2006) it is even more unlikely that massive elliptical galaxies could have formed from binary disc mergers in the past.

Furthermore it has been shown that the stellar populations of massive ellipticals have not only formed at high redshift but also on short timescales (e.g. Heavens et al. 2004; Thomas et al. 2005). This is not compatible with the long formation timescales of disc galaxies. The problem is less severe for low mass ellipticals which have more extended formation timescales and even show signs of young stellar populations (Thomas et al. 2003). An additional complication is that elliptical galaxies predominantly populate high density regions like galaxy clusters (Hubble & Humason 1931; Hubble 1937), whereas disk galaxies populate the field and the overdensity is independent of their luminosity at a given color (Hogg et al. 2003). The morphology-density relationship seems to be valid over several magnitudes in density (Melnick & Sargent 1977; Dressler 1980; Postman & Geller 1984; Whitmore & Gilmore 1991) and the most massive ellipticals live in the highest density environments (Hogg et al. 2004). In summary, the mass of spiral galaxies is a very weak function of environment, early type galaxies are predominantly found in high density regions and the more massive the galaxy the higher the overdensity. With the exception of accretion onto the central cluster galaxy, mergers are not likely in clusters, therefore in the simplest form of the merger scenario a typical $10^{12} M_\odot$ elliptical must have formed from a merger of two $5 \times 10^{11} M_\odot$ disc galaxies outside of the cluster, and the hypothesized progenitor spirals are rare or nonexistent at any observed epoch.

In the following we present a model for the evolution of a typical spiral galaxy with a central bulge component and address several of the above questions using an idealised scenario of a binary merger of our model galaxy and its progenitors.

4 THE MODEL FOR BULGE AND DISK FORMATION

In this section we describe the simple Naab & Ostriker (2006) model for the formation of the Milky Way disc where we added to our previous treatment the formation of a luminous central bulge component. The model reproduces nicely observable properties of the present day Milky Way without the explicit inclusion of detailed feedback processes (e.g. Efstathiou 2000) which have their main impact at the early phases of disk evolution (Johansson & Efstathiou 2006). We assume that in the absence of star formation the gas in a given halo would settle in a disc with an exponential surface density

$$\Sigma_d(r, t) = \Sigma_0(t) \exp[-r/r_d(t)],$$

(1)

where the central surface density $\Sigma_0(t)$ and the scale length $r_d(t)$ can change with time. The galactic disk starts to form after the halo has reached its present day virial velocity at its formation time $t_{form}$. Thereafter it decouples from the general merging. After the decoupling the central surface density is fixed to the present day value while the scale length $r_d(t)$ is allowed to change as a fixed fraction $f_{r,d}(t)$ of the virial radius $r_{vir}$ of the halo

$$r_d(t > t_{form}) = f_{r,d} \frac{r_{vir}(t_{form})}{10H(t)},$$

(2)

where

$$H(z) = H_0[\Omega_{A,0} \Omega_0 + (1-\Omega_{A,0}-\Omega_0)(1+z)^2 + \Omega_0 (1+z)^3]^{1/2},$$

(3)

is the Hubble parameter at redshift $z$.

At earlier times $t < t_{form}$ when the galaxy is still coupled to the hierarchical growth the gas will have lost its angular momentum more effectively due to shocks and tidal torques resulting in a smaller collapse fraction $f_{c,b}$. We associate this phase with the formation epoch of the bulge. For simplicity we assume that the gas also settles in an exponential surface density profile. The spheroidal stellar component might form from dynamical instabilities or tidal interactions which we do not follow explicitly in our model. The scale length of the gas then evolves as

$$r_b(t < t_{form}) = f_{r,b} r_{vir}(t) = f_{r,b} \frac{r_{vir}(t)}{10H(t)},$$

(4)

and rotation velocity of the 'bulge' peaks at a radius of $r_{2,2}(t) = 2.15r_b(t)$ at a value of $v_{b,2,2}(t) = 0.774\pi \Sigma_0(t)r_b(t)$.

Using the similar scalings as in Naab & Ostriker (2006) the central surface density will increase as

$$\Sigma_0(t < t_{form}) = \frac{\alpha}{\pi G} 10H(t)v_c(t),$$

(6)

with $\alpha = 3.6$ that has been scaled to result in a peak rotation velocity the Milky Way bulge of 250 km/s assuming a present day value of $v_c = 210$ km/s at large radii. The total surface density of the system has been scaled to a present day value of $50 M_\odot pc^{-2}$ at $r = 8 kpc$.

At this point we have to include a model for star formation to the model to follow the evolution of the stellar and gaseous phase separately. After the gas within a halo has settled it starts forming stars. We use a formulation based on the local dynamical time (rotation period) of the system (Kennicutt 1989). At every radius the surface density of the star formation rate is given by

$$\Sigma_{SFR}(r, t) = \frac{\epsilon \Sigma_{gas}(r, t)}{r_{orb}(r, t)}$$

(7)
We follow the chemical evolution of the model galaxies in independent rings assuming no radial gas flows using a modified version of the chemical evolution model of Ostriker & Tinsley (1975). In every ring the change in gas surface density $\Sigma_g$ and surface density in stars $\Sigma_s$ is given by

$$d\Sigma_g(r, t) = -\Sigma_{SFR}(r, t) dt + K_{\text{ins}}(r, t) dt + K_{\text{late}}(r, t) dt + \Sigma_{\text{IFR}}(r, t) dt$$

$$d\Sigma_s(r, t) = \Sigma_{\text{SFR}}(r, t) dt - K_{\text{ins}}(r, t) dt - K_{\text{late}}(r, t) dt,$$

where $\Sigma_{\text{SFR}}$ is the star formation rate per unit area (Eqn. 7) and $\Sigma_{\text{IFR}}$ is the rate of gas infall onto the galaxy per unit area, as defined in Eqn. 7. $K_{\text{ins}}$ is the mass per unit area in gas ejected from massive stars instantaneously, $K_{\text{late}}$ is the mass per unit area in gas ejected at later evolutionary phases of low mass stars. They are defined as

$$K_{\text{ins}}(r, t) = R_{\text{ins}}\Sigma_{\text{SFR}}(r, t),$$

$$K_{\text{late}}(r, t) = \int_0^t \Sigma_{\text{SFR}}(t', r) W(t - t') dt'.$$

$R_{\text{ins}} = 0.1$ is the fraction of gas returned instantaneously to the ISM from newborn massive stars and $W(t)$ is a weighting function defined as

$$W(t) = R_s \frac{\delta_s - 1}{\tau_0} \left( \frac{t}{t + \tau_0} \right)^{\delta_s}$$

with $R_s = 0.3$, $\delta_s = 1.36$, and $\tau_0 = 1 \times 10^9$ assuming a Salpeter (1955) IMF (Ciotti et al. 1991). This analytic expression is a good approximation for the fraction of returned gas for a single burst population to the metal dependent values of the spectral evolution model by Bruzual & Charlot (2003) that we have used to compute the photometric properties of the model disc (see Naab & Ostriker 2006). More detailed description of this model will be given in a separate paper.

4.1 Assembly history

The upper panel in Fig. 1 shows the evolution of the total mass in gas and stars, respectively. The galaxy rapidly assembles mass after $z = 3$, which is the bulge formation phase, thereafter the disk is growing. At present the total mass of the disc out to 26kpc is $M_{\text{tot}} \approx 6 \times 10^{10} M_\odot$ with about $M_g = 1 \times 10^{10} M_\odot$ in gas and $M_{\text{tot}} = 5 \times 10^{10} M_\odot$ in stars. The time evolution of the local surface density is shown in the lower plot in Fig. 1. The model has been normalised to a present day total surface density of $50 M_\odot \text{pc}^{-2}$. The gas starts to assemble at the solar radius after 3Gyrs, and after 6Gyrs the local gas surface density stays almost constant at its present day value of $15 M_\odot \text{pc}^{-2}$. The first stars at the solar radius form after 3Gyrs followed by a steady increase to the present day value of $35 M_\odot \text{pc}^{-2}$ (with $\approx 3 M_\odot \text{pc}^{-2}$ invisible in stellar remnants) resulting in $\approx 3 M_\odot \text{pc}^{-2}$ visible stars. These numbers are identical to those given in Naab & Ostriker (2006) as is the local star formation history at the solar radius. Therefore the evolution of the outer disk is not affected by the bulge evolution.

The evolution of the total star formation and infall rate of the model galaxy is shown in Fig. 2. The peak in both
rates at $3 < z < 2$ indicates the period of the formation of the bulge with infall rates as high as $90 M_\odot yr^{-1}$ and star formation rates of $\approx 30 M_\odot yr^{-1}$. It is interesting that this analytical treatment of the formation of the galactic bulge parallels to a surprising degree the detailed hydrodynamical simulations of an elliptical galaxy by Naab et al. (2007) from cosmological initial conditions. Thereafter the rates drop rapidly to values close to their present day numbers of $2 - 3 M_\odot yr^{-1}$ for the infall rate and $\approx 3 M_\odot yr^{-1}$ for the star formation rate.

As mentioned before, the evolution of the model galaxy at the solar radius is not changed by the inclusion of the bulge. Therefore the metallicity distribution is the same and in Naab & Ostriker (2006) and is in good agreement with observations. To compute the metallicity evolution we have used the solar metallicity value of $Z_\odot = 0.0126$ to scale our model to $0.1$ dex below the solar metallicity $Z = Z_\odot \times 10^{-0.1} = 0.01$ at solar radius $4.5Gyrs$ ago, resulting in an effective yield of $Y = 0.0135$ (see Naab & Ostriker 2004).

Fig. 3 shows the radial metallicity distribution of the ISM and the stars of the model galaxy. The distribution after 2, 4, 6, 8, 10, and 12Gyrs is indicated by the dotted (gas) and solid (stars) lines. At the solar radius the metallicity gradient is similar to the pure disc model of Naab & Ostriker (2006), however, at smaller radii the metallicity of the gas and the stars is significantly higher.

4.2 Photometric properties

To compute the photometric properties of our model galaxy we use the Bruzual & Charlot (2003) models for spectral evolution of stellar populations assuming a Salpeter IMF. Fig. 4 shows the time evolution of the absolute magnitudes, the total luminosities and the colours of the model galaxy at different wavelengths. All values are in reasonable agreement with observations. The surface brightness profiles at different wavelengths are shown in the upper panel of Fig. 4. Two observed values in the K- and B-band at the solar radius are overplotted (Binney & Merrifield 1998). The middle panel shows the corresponding luminosity density profiles using the solar magnitudes given above. All profiles are exponential in the outer parts. The color profiles with two observational value at the solar radius are shown in the bottom panel of Fig. 4. We have performed a bulge-disc decomposition using the fitting model described in Naab & Trujillo (2006) and find a bulge to total ratio of $B/T=0.2$ in reasonable agreement with estimates for the Milky Way.

To calculate the scale lengths in the different bands we have fitted an exponential in the range of $1 < r_d < 3$ scale lengths of the total surface density distribution. The scale lengths increase to shorter wavelengths (Fig. 4). This effect is weaker at earlier times. At present the B-band scale length $r_{d,B} = 3.7kpc$ is a factor of $\approx 1.2$ larger than the K-band scale length $r_{d,K} = 3.0kpc$. This trend is observed and is in good agreement with other Milky Way type spiral galaxies. de Jong (1996) investigated a sample of 86 nearly
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5 THE IDEALISED DISC MERGER

Numerical studies in the past have shown that sizes, photometric properties and dynamics of disk merger remnants are in reasonable agreement with the properties of observed intermediate mass giant elliptical galaxies. Using the model for galaxy evolution described in the previous section we now have a self consistent model giving knowledge about the evolution of a typical disc galaxy, e.g. ages and metallicities of the stars and gas content at any redshift. Using this information we can investigate the remnant properties in an idealised disc galaxy merger scenario. We assume that two identical disk galaxies (with or without bulges) merge at different times in the past and investigate the integrated properties of their combined stellar populations today. During the merger we allow all gas within two disc scale lengths to be transformed into stars in a single burst. After the galaxies have merged we assume that further star formation is suppressed. This might either be due to the heating of gas by supernovae, AGN feedback, shock heating of infalling gas, the infall of the remnant into a cluster or a combination of all effects. As we know the properties of the stars and the gas content of the progenitors disks at any redshift, we can predict the present day properties of the stellar population of the remnant that has formed by a merger at any time in the past.

In Figure 7 we show the present day location of the merger remnants of two Milky Way like galaxies in the $U-V$ color-magnitude diagram. For every merger model the rightmost symbols represents the properties of the present day merger. Following the symbols for every model from the right to the left we have placed the merger further back in the past. The observed UV color-magnitude diagram of elliptical galaxies is overplotted (McIntosh et al. 2007). In the two upper panels we show the properties of a merger of pure disks with and without a burst assuming the Naab & Ostriker (2006) model. It is evident that a present day merger of disk galaxies results in a remnant that is far too blue to be an elliptical galaxy. The discrepancy is even stronger if we consider the young population of stars created in a burst during the merger. Placing the merger further back in time results in a present day remnant that becomes less luminous and redder. Taking the spread in...
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Figure 7. Upper panel: $U - V$ color versus absolute magnitude $M_V$ of the stellar populations of two pure disk galaxies added together in an idealized merger at different times in the past. The triangles show the properties for the stellar remnant alone. The asterisks show the remnant properties assuming that all gas within two scale lengths at the given time was transformed into stars in a single burst. The burst and no-burst models are connected by a dotted line. The present day burst model is off the scale. The rightmost pair indicates the properties of a present day merger remnant. Every pair further to the left shifts the merger event one Gyr further back into the past. Lower panel: Same as above but for progenitor disks with bulges. All remnants are consistent with the CM-relation if the merger would have taken place 3 Gyrs ago or earlier. 5 Gyrs or older mergers of disk galaxies with bulges lead to the most consistent results. Mergers of present day disks do not fall on the CM-relations independent of their properties.

As in the disk-only case we have to place the merger event at least 3 Gyrs in the past to be consistent with the present day UV CM-relation. The 5 Gyr old merger falls right on the correlation as in the pure disk case and produces an elliptical having a current magnitude of $M_V = -20.6$. In contrast to the disk-only models, all earlier mergers fall on the color-magnitude relations due to the presence of the massive old bulge component. However, at higher redshifts $z > 1$ it is a merger of two bulge dominated galaxies and not a disc merger, i.e. to a significant extend we are considering the merger of ellipticals to make new ellipticals.

In Fig. 8 we show the mean age of the stellar population of the merger remnant at different lookback times for the models with and without a bulge component. For a 5 Gyr old merger (which corresponds to a merger redshift of $z \approx 0.5$) the disk-only remnant has a mean age of 7.9 Gyrs. The remnant with bulges in the progenitor disks would be significantly older with a mean age of 9.2 Gyrs.

Our model Milky Way galaxy with bulge is about two times more massive than a typical present day disc galaxy. If we, however, assume that the backward evolution with time is typical for disk galaxies of similar mass, and there is observational evidence for that [Barden et al. 2005], we can scale our model down and follow the evolution of the mass in metals for a typical disk merger backwards in time. In Fig. 9 we have scaled the model to a present day total stellar mass of $2.9 \times 10^{10} M_\odot$ (see Section 3) and compare the mass in metals of disc mergers with and without bulge to present day ellipticals. At present, disc merger remnants have $\approx 2.4 - 3.1$ times less mass in metals if they contain bulge components. Without bulges this value becomes as large as 6-8 at the present day and even larger at higher redshifts. The bulge, although less massive than the disk itself is significantly more metal rich, in line with our previous arguments. Therefore the total mass in metals is about a factor of two higher for the model with bulge. Assuming a burst during the merger does not change the overall values much as the total gas fraction of the progenitor galaxies stays at a constant fraction of $\approx 20\%$ since $z=2$. The metal
Figure 9. Evolution of the mass in metals for merger of two $M_*$ disk galaxies based on the model presented in the paper with (solid) and without (dashed) a bulge component. The total mass of the progenitor disks has been scaled to $2.9 \times 10^{10} M_\odot$. The mass in metals for $M_*$ ellipticals is indicated by the shaded area. At present ellipticals have at least a factor of two more mass in metals.

The mass of ellipticals could only be reached if all available gas would be transformed into stars with eight times the solar metallicity during the merger.

6 CONCLUSION AND DISCUSSION

In this paper we have addressed the question of whether elliptical galaxies can have formed from binary mergers of disc galaxies. At present typical disc galaxies have lower stellar masses, lower masses in metals, younger stellar populations and more extended star formation histories than elliptical galaxies. In addition they populate different environments. The first simple conclusion is that mergers of present day spiral galaxies, like our Milky Way, can not form typical present day ellipticals but some subset of future ellipticals having $L \leq L_*$ may form in this fashion right now. In fact nearby ULIRGS are disc mergers with mass ratios of 1:1 to 3:1 (Dasyra et al. 2006) and they show kinematical and isophotal properties similar to present day intermediate mass ellipticals (Genzel et al. 2000; Rothberg & Joseph 2002; Dasyra et al. 2006). After their stellar populations have aged for $\approx 4$ Gyr they will add to the population of intermediate mass ellipticals. Expanding the investigation to cosmic history we have used a theoretical model for mergers of a typical Milky Way spiral at different epochs to put more general constraints on binary merger scenario.

We find that mergers of progenitors of present day spiral galaxies can have stellar populations comparable to present day low and intermediate mass elliptical galaxies if they have merged more than 3.5 Gyr ago ($z > 0.3$) and have their star formation turned off after the merger event. Any further star formation after the merger will shift, the time for the merger event further into the past. The progenitors of mergers before $z=0.3$, however, have smaller sizes ($r \leq 2.5$ kpc), smaller stellar masses $(M < 4 \times 10^{10} M_\odot)$ and are more bulge dominated than at present. As we know from a large number of numerical studies (see Section 5) these will have sizes and kinematical properties similar to intermediate mass ($M_*$) ellipticals. And early mergers of spiral galaxies will lead to ellipticals having metal masses far below those seen in present day $L_*$ ellipticals.

Specifically, if the merger takes place further back in the past, say at $z=1$, the typical sizes of discs will be $(r \leq 2$ kpc) with stellar masses $M < 3 \times 10^{10} M_\odot$. However, the typical mass in metals will be a factor of 4-8 smaller than typical present day ellipticals, and, even worse, at $z = 2$ the mass in metals will be a factor of 10-18 smaller and the merger progenitors will be small and bulge dominated. This epoch, however, is supposed to be the main formation epoch of ellipticals, especially the most massive ones.

We therefore draw the following conclusion: Typical massive giant ellipticals (more massive than $M_*$) can neither be made from binary mergers of present day spirals nor from their progenitors although some subset of the total observed $z=0$ elliptical galaxy population is certainly produced by such mergers. Most of them must be made from either multiple mergers (Li et al. 2006) or binary mergers of spirals at early times whose descendents no longer exist. Any scenario addressing the full mass range of ellipticals that is based on binary mergers, e.g. for the origin of the black-hole-mass velocity-dispersion relation (Di Matteo et al. 2003), will have to account for this conclusion. However, there is clear evidence that dissipation played an important role during the formation of the spheroids especially at lower masses (see e.g. Kormendy 1989; Bender et al. 1992; Kormendy & Bender 1996; Dekel & Cox 2006; Naab et al. 2006; Khochfar & Silk 2006a; Ciotti et al. 2006; Naab et al. 2007). However, even massive ellipticals with rotation supported, old and metal rich kinematically decoupled cores show clear signs of dissipation (Bender & Surma 1993; Surma & Bender 1993; Davies et al. 2001; McDermid et al. 2004).

Major binary mergers of early-type galaxies might play an important role for the final assembly of massive ellipticals (Khochfar & Burkert 2003; Robertson et al. 2006; Boylan-Kolchin et al. 2006; Bell et al. 2006; Naab et al. 2006; Bell et al. 2006) but they can not connected to the formation of the spheroids in the first place.

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