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MINOR MERGERS AND THE SIZE EVOLUTION OF ELLIPTICAL GALAXIES

Thorsten Naab[1], Peter H. Johansson[1], and Jeremiah P. Ostriker[2]
[1] Universitäts-Sternwarte München, Scheinerstr. 1, D-81679 München, Germany; naab@usm.lmu.de
[2] Department of Astrophysics, Peyton Hall, Princeton University, Princeton, NJ 08544-1001, USA
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ABSTRACT

Using a high-resolution hydrodynamical cosmological simulation of the formation of a massive spheroidal galaxy we show that elliptical galaxies can be very compact and massive at high redshift in agreement with recent observations. Accretion of stripped infalling stellar material increases the size of the system with time and the central concentration is reduced by dynamical friction of the surviving stellar cores. In a specific case of a spheroidal galaxy with a final stellar mass of $1.5 \times 10^{11}\ M_{\odot}$ we find that the effective radius r_e increases from 0.7 ± 0.2 kpc at $z = 3$ to $r_e = 2.4 \pm 0.4$ kpc at $z = 0$ with a concomitant decrease in the effective density of an order of magnitude and a decrease of the central velocity dispersion by approximately 20% over this time interval. A simple argument based on the virial theorem shows that during the accretion of weakly bound material (minor mergers) the radius can increase as the square of the mass in contrast to the usual linear rate of increase for major mergers. By undergoing minor mergers compact high-redshift spheroids can evolve into present-day systems with sizes and concentrations similar to observed local ellipticals. This indicates that minor mergers may be the main driver for the late evolution of sizes and densities of early-type galaxies.

Key words: galaxies: elliptical and lenticular, cd – galaxies: evolution – galaxies: interactions – galaxies: structure – methods: numerical

1. INTRODUCTION

There is recent observational evidence that a significant fraction of massive evolved spheroidal stellar systems is already in place at redshift $z \geqslant 2$. However, only a small percentage of these galaxies is fully assembled (van Dokkum et al. 2008). The galaxies are smaller by a factor of 3–5 compared to present-day ellipticals at similar masses (Daddi et al. 2005; Longhetti et al. 2007; Toft et al. 2007; Trujillo et al. 2007; van Dokkum et al. 2008; Cimatti et al. 2008; Saracco et al. 2009). Their effective stellar mass densities are at least 1 order of magnitude higher (van Dokkum et al. 2008; Damjanov et al. 2009) with significantly higher surface brightnesses compared to their low-redshift analogs (Cimatti et al. 2008).

These observations are difficult to reconcile with some current idealized formation scenarios for elliptical galaxies. A simple conclusion from the data is that most early-type galaxies can neither have fully formed in a simple monolithic collapse nor a binary merger of gas-rich disks at high redshift, unless their increase in size can be explained by secular processes such as adiabatic expansion driven by stellar mass loss and/or strong feedback (Damjanov et al. 2009; Fan et al. 2008). Additionally, simple passive evolution of the stellar population is in contradiction with observations of local ellipticals (van Dokkum et al. 2008).

Dry (i.e., gas-poor, collisionless) mergers and stellar accretion events are the prime candidates for the strong mass and size evolution of stellar spheroids at $z < 2$ (Naab et al. 2006; Khochfar & Silk 2006; Bell et al. 2006a, 2006b; Ruszkowski & Springel 2009; Hopkins et al. 2009; van der Wel et al. 2009) as the additional presence of a dissipative component in a major merger event would limit the size increase (see, e.g., Ciotti et al. 2007). The observed ellipticals are already very massive at high redshift, thus we expect from the shape of the mass function that minor mergers should be much more common than major mergers until $z = 0$.

Massive early-type galaxies may undergo not more than one major merger (with typically low cool gas content, see also Whitaker & van Dokkum 2008) since $z = 0.7$ (Bell et al. 2006b, see also McIntosh et al. 2008) with a significant contribution from minor mergers for the mass buildup (Bundy et al. 2009). The low number of observed major early-type mergers is also supported by theoretical evidence that massive ($\approx 10^{11-12}\ M_{\odot}$) halos at $z = 2$ typically experience only one major merger or less until $z = 0$ and minor mergers are much more common (Genel et al. 2008b; Khochfar & Silk 2008). On average, this is not enough to account for the required mass and size growth (see also Damjanov et al. 2009) as major dry mergers at most increase the size of a simple one-component system by a factor of 2 and allowing for dark matter halos reduces the size growth further (Nipoti et al. 2003; Naab & Trujillo 2006; Hopkins et al. 2008).

In this Letter we use, as a proof of principle, a very high resolution cosmological simulation of the formation of a spheroid with no major mergers below $z = 3$ in combination with simple scaling relations to show that the observed rapid size growth and density evolution of spheroidal galaxies can be explained by minor mergers and small accretion events. The problem is computationally very expensive. At high redshift the observed ellipticals have half-mass sizes of < 1 kpc with accreting subsystems of even smaller size. As we know from isolated merger simulations (see, e.g., Naab & Burkert 2003), to resolve such a system reasonably well we require a force softening of 10% of the effective radius, which in our case is of the order of 100 pc and we require particle numbers of $\approx 10^7$ to simulate the galaxy in a full cosmological context over a Hubble time. Finally, to accurately follow the kinematics high force and integration accuracy are required.

2. SIZE EVOLUTION AND MINOR MERGERS

Using the virial theorem we make a simple estimate of how an initial one-component stellar system evolves when mass in stellar systems is added. We assume that a compact initial stellar system has formed dissipatively from stars. This system has a total energy E_i, a mass M_i, a gravitational radius $r_{g,i}$, and the mean square speed of the stars is $\langle v_i^2 \rangle$. According to the virial theorem (Binney & Tremaine 2008) the total energy of the system is

$$E_i = K_i + W_i = -K_i = \frac{1}{2}W_i = -\frac{1}{2}M_i\langle v_i^2\rangle = -\frac{1}{2}\frac{GM_i^2}{r_{g,i}}. \quad (1)$$

We then assume that systems are accreted with energies totaling E_a, masses totaling M_a, gravitational radii $r_{a,i}$, and mean square speeds averaging $\langle v_a^2 \rangle$. We define the fractional mass increase from all the accreted material $\eta = M_a/M_i$ and the total kinetic energy of the material as $K_a = (1/2)M_a\langle v_a^2\rangle$, further defining $\epsilon = \langle v_a^2\rangle/\langle v_i^2\rangle$. Assuming energy conservation (orbital parameters from cosmological simulations (Khochfar & Burkert 2006) indicate that most halos merge on parabolic orbits), the total energy of the final system is

$$\begin{aligned} E_f = E_i + E_a &= -\frac{1}{2}M_i\langle v_i^2\rangle - \frac{1}{2}M_a\langle v_a^2\rangle \\ &= -\frac{1}{2}M_i\langle v_i^2\rangle - \frac{1}{2}\eta M_i\epsilon\langle v_i^2\rangle \\ &= -\frac{1}{2}M_i\langle v_i^2\rangle(1+\epsilon\eta) \\ &= -\frac{1}{2}M_f\langle v_f^2\rangle. \end{aligned} \quad (2)$$

The mass of the final system is $M_f = M_i + M_a = (1+\eta)M_i$. Therefore, the ratio of the final to initial mean square speeds is

$$\frac{\langle v_f^2\rangle}{\langle v_i^2\rangle} = \frac{(1+\eta\epsilon)}{1+\eta}. \quad (3)$$

Similarly, the ratio of the final to initial gravitational radius is

$$\frac{r_{g,f}}{r_{g,i}} = \frac{(1+\eta)^2}{(1+\eta\epsilon)} \quad (4)$$

and for the ratio of the densities we obtain

$$\frac{\rho_f}{\rho_i} = \frac{(1+\eta\epsilon)^3}{(1+\eta)^5}. \quad (5)$$

If during one or more mergers the initial stellar system increases its mass by a factor of 2 then $\eta = 1$. This mass increase can be caused by one equal-mass merger in which case the mean square velocities of the two systems are identical and remain unchanged in the final system (Equation (3)). The radius increases by a factor of 2 (Equation (4)) and the density drops by a factor of 4 (Equation (5); see also Hopkins et al. 2009). If, however, the total mass increase by a factor of 2 is caused by the accretion of very small systems with $\langle v_a^2\rangle \ll \langle v_i^2\rangle$ or $\epsilon \ll 1$, then the mean square velocities are reduced by a factor of 2, the radius is four times larger and the density is reduced by a factor of 32 with respect to the initial system (see also Bezanson et al. 2009 for a similar derivation of the scaling relations). We know from the shape of the Schechter function for the distribution of stellar masses that a massive system ($m > M_*$) accretes most of its mass from lower mass systems and thus the simple calculation above makes it very plausible that even though major mergers do occur, minor mergers are the main driver for the evolution in size and density of massive galaxies.

3. HIGH-RESOLUTION SIMULATIONS OF AN INDIVIDUAL GALAXY HALO

We have performed a cosmological N-body/smoothed particle hydrodynamic (SPH) high-resolution re-simulation of an individual galaxy halo. The process of setting up the initial conditions is described in detail in Naab et al. (2007) and is briefly reviewed. We have re-run galaxy A at 200^3 particles resolution using a WMAP-1 (Spergel et al. 2003) cosmology with a Hubble parameter of $h = 0.65$ ($\equiv H_0 = 100\,h$ km s^{-1} Mpc^{-1}) with $\sigma_8 = 0.86$, $f_b = \Omega_b/\Omega_m = 0.2$, $\Omega_0 = 0.3$, and $\Lambda_0 = 0.7$. To re-simulate the target halo at high resolution we increased the particle number to 1.6×10^7 gas and dark matter particles within a cubic volume at redshift $z = 24$ containing all particles that end up within the virialized region (we assumed a fixed radius of 0.5 Mpc) of the halo at $z = 0$. The tidal forces from particles outside the high-resolution cube were approximated by increasingly massive dark matter particles in five nested layers of decreasing resolution. The galaxy was not contaminated by massive boundary particles within the virial radius.

The simulation was performed with GADGET-2 (Springel 2005) on Woodhen at the Princeton PICSciE HPC center using a total of 177,000 CPU hr on 64 CPUs. We used a fixed comoving softening until $z = 9$, and thereafter the softening, e.g., for the stars, remained fixed at physical 125 pc. The mass of an individual stellar particle is $1.3 \times 10^5\ M_\odot$ and we spawn two stars per SPH particle.

Star formation and feedback from supernovae was included using the subgrid multiphase model of Springel & Hernquist (2003). We require an overdensity contrast of $\Delta > 55.7$ for the onset of star formation to avoid spurious star formation at high redshift. The threshold number density for star formation is $n_{\mathrm{thresh}} = 0.205\,\mathrm{cm}^{-3}$ and the star formation timescale is $t_* = 1.5\,h^{-1}$ Gyr. We also included a uniform UV background radiation field peaking at $z \simeq 2$–3 (see Naab et al. 2007).

At present the galaxy has a total virial mass of $1.9 \times 10^{12}\ M_\odot$ and a total stellar mass of $1.5 \times 10^{11}\ M_\odot$. The ratio of central stellar mass to halo mass is about a factor of 2 larger than predicted from gravitational lensing studies (Mandelbaum et al. 2006), however, it is comparable to some recent predictions derived for the Milky Way halo (e.g., Xue et al. 2008, see however Li & White 2008). The central stellar component resembles an elliptical galaxy with properties very similar to the results presented in Naab et al. (2007) and in this Letter we focus only on particular aspects of the assembly and size evolution of the stellar component.

4. RESULTS

During the assembly of the central galaxy we have separated the stars within a fiducial radius of 30 kpc in fixed physical coordinates into stars that have formed in situ from gas within the galaxy and stars that have formed outside this radius and were accreted later on. The mass assembly histories of the in situ and accreted components of the stellar system are shown in Figure 1. The early mass evolution at $z > 2$ is driven by the assembly of in situ stars with a decreasing contribution toward $z \approx 0.7$. Below this redshift only few stars are formed within 30 kpc. The final 20% of the stars are added thereafter by accretion of systems formed outside the main stellar system at radii larger than 30 kpc.

The upper panel of Figure 2 shows the density profiles of the in situ stars at redshifts $z = 5, 3, 2, 1, 0$. Between $z = 5$ and $z = 3$ the central galaxy is still building up from gas flows feeding

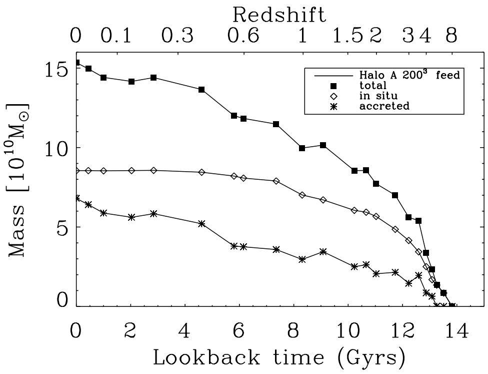

Figure 1. Mass assembly history of the stellar system (squares) separated into stars made in situ (open diamonds) in the galaxy and stars formed outside the galaxy that have been accreted (stars) later on. At high redshift ($z > 2$) the system assembles by the formation of in situ stars, at low redshift ($z < 1$) accretion is more dominant.

the central region of the galaxy directly, forming a concentrated stellar system. The in situ central stellar densities decrease by more than an order of magnitude toward lower redshifts. The spherical half-mass radii of the in situ stellar component, show that the in situ system is very compact (see also Joung et al. 2009) at $z = 3$ (0.5–0.6 kpc) and its size increases by about a factor of 4 (≈ 2 kpc) until $z = 0$. In the bottom panel of Figure 2, we show the density profiles for the stars that have formed outside 30 kpc and have been accreted later on. This component is more extended at all redshifts and has a shallower density profile. Its central density stays almost constant at $\approx 10^{10}\ M_\odot\ \mathrm{kpc}^{-3}$ while the density at larger radii subsequently increases toward $z = 0$. The half-mass radius of this component is significantly larger than for the in situ stars (> 3 kpc). The central part of the galaxy is always dominated by in situ stars whereas at redshifts below $z \approx 2$–3 and at radii larger than ≈ 2–3 kpc the system is dominated by accreted stars.

In Figure 3, we show the time evolution of the edge-on projected half-mass radius of stars in the central galaxy within the central physical 30 kpc as a function of time. At $z = 3$ the stellar system resembles a compact disk-like or bar-like object with a peak ellipticity of $\epsilon = 0.65$ and a size of ≈ 0.3–0.7 kpc at $z = 3$. Thereafter its size increases by a factor of ≈ 3–4 to its present value of 2.7 kpc. We also plot the projected half-light radii in the rest frame K- and V-band using the stellar population models of Bruzual & Charlot (2003) assuming solar metallicity. In general, the half-mass radii trace the half-light radii even at larger redshifts reasonably well.

The K-band rest-frame surface brightness profiles for edge-on projections at $z = 0$ and $z = 3$ are shown in Figure 4 in combination with the best-fitting Sérsic profiles. using the fitting procedure of Naab & Trujillo (2006) excluding the central three softening lengths. At high redshift the system is very compact, $r_e = 0.69$ kpc, and has a moderate Sérsic index of $n \approx 2.3$. This is in agreement with the system being flattened and disk-like. At low redshift the system is more extended $r_e = 2.4$ kpc, and its Sérsic index has increased to $n = 3.3$. The galaxy is slightly more compact than typical Sloan Digital Sky Survey (SDSS) early-type galaxies at this mass but lies within the observed distribution (Shen et al. 2003, see also Franx et al. 2008). The errors given in the figure are bootstrap errors for a fixed projection. As we have shown before the evolution in surface brightness is mainly driven by an evolution in surface density and not by stellar evolution.

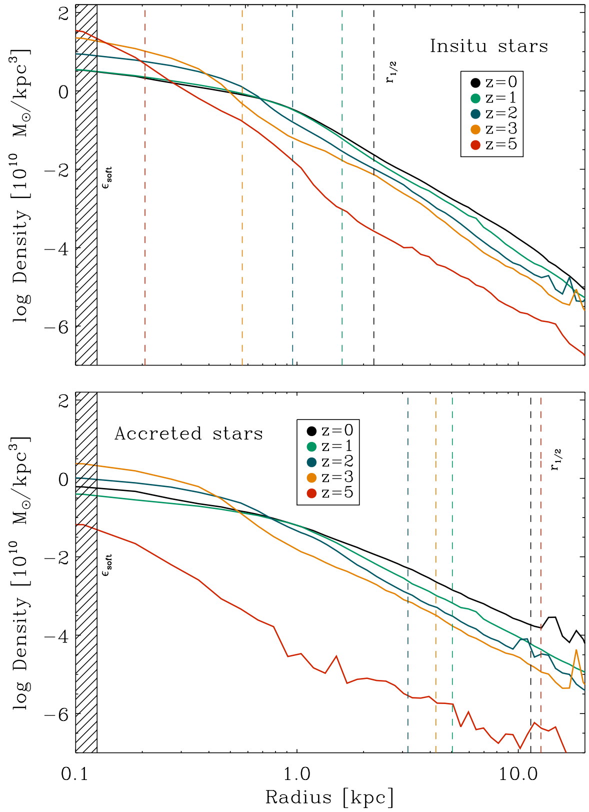

Figure 2. Density profile of the stars formed in situ in the galaxy (upper plot) and of stars formed outside the galaxy and then accreted later on (bottom plot) at redshifts $z = 5, 3, 2, 1, 0$ (red, orange, blue, green, black). The spherical half-mass radii $r_{1/2}$ are indicated by the dashed vertical lines. The shaded area indicates the gravitational softening length.

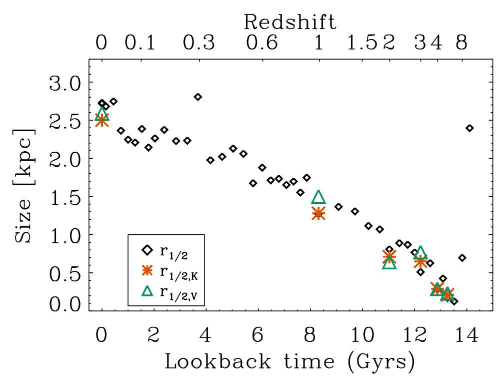

Figure 3. Time evolution of the edge-on circular projected stellar half-mass radius within fixed physical 30 kpc (black diamonds). From $z = 3$–2 to $z = 0$ the size increases by a factor of ≈ 3–4. We also show the evolution of the rest-frame K-band (red cross) and V-band (green triangle) half-light radius. Outliers indicate minor merger events, e.g., the most massive (8:1) merger since $z = 3$ at $z = 0.3$.

At $z = 3$ the system has a total stellar mass of $M = 5.5 \times 10^{10}\ M_\odot$ with an effective radius $r_{\mathrm{eff}} = 0.69$ kpc and a corresponding effective density of $\rho_{\mathrm{eff}} = 0.5M/(4/3\pi r_{\mathrm{eff}}^3) = 1.6 \times 10^{10}\ M_\odot$. The projected stellar line-of-sight velocity dispersion is $\sigma_{\mathrm{eff}} \approx 240\ \mathrm{km\ s}^{-1}$. The corresponding values at $z = 0$ are $M = 15 \times 10^{10}\ M_\odot$, $r_{\mathrm{eff}} = 2.4$ kpc, $\rho_{\mathrm{eff}} = 1.3 \times 10^9\ M_\odot$, and $\sigma_{\mathrm{eff}} \approx 190\ \mathrm{km\ s}^{-1}$, which is a typical dispersion for early-type galaxies at this mass (Bender et al. 1992). From $z = 3$ to $z = 0$ the system accretes about $5.5 \times 10^{10}\ M_\odot$ (see Figure 1) and we can assume for the above

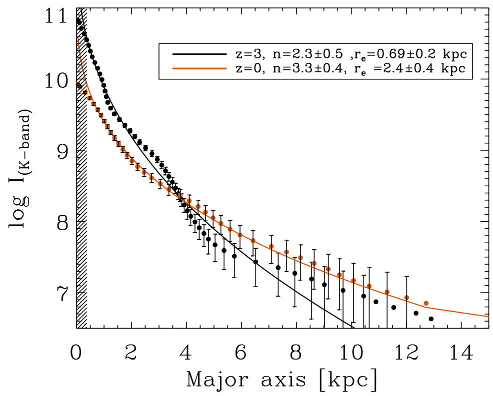

Figure 4. *K*-band surface brightness profiles assuming solar metallicity at $z = 3$ (black dots) and $z = 0$ (red dots). The black and red lines indicate the best-fitting Sérsic profile. At high redshift the galaxy has a higher central surface brightness and is more compact.

scaling relations $\eta = 1$ and $\epsilon \ll 1$ (which is a reasonable assumption as most mass is accreted in very small systems and we found the most massive merger since $z = 3$ with a mass ratio of 8:1). The $z = 0$ values of the simulated galaxy are close to the simple prediction, however, the size increase as well as the decrease in density and dispersion are more moderate. This is however expected as the real evolution of the system is more complex and there is non-negligible in situ star formation between $z = 3$ and $z = 1$. Still, the simple scaling relations for stellar accretion represent the evolution of the system from $z = 3$ to $z = 0$ very well. However, observations of more massive ellipticals than the one presented here indicate an even stronger size increase (Franx et al. 2008). This effect can be expected if the assembly of more massive galaxies is even more dominated by minor mergers and stellar accretion.

In particular, the drop in velocity dispersion is in qualitative agreement with first direct observations by Cenarro & Trujillo (2009). Recently, Bezanson et al. (2009) reported a relatively weak evolution of the density within fixed 1 kpc of only a factor 2–3. This also is in qualitative agreement with our simulation which shows a decrease of only a factor 1.5 from $z = 2$ to $z = 0$. We also note that the stellar population of the system is already evolved at high redshift. At $z = 2$ the galaxy has a stellar mass of 7.5×10^{10} $M_\odot$ and a local star formation rate of only ≈ 6 $M_\odot$ yr^{-1} and an average stellar age of 1.6 Gyr.

5. CONCLUSION AND DISCUSSION

In this Letter, we show that the observed size and density evolution of massive spheroids agrees with what is to be expected from a high-resolution cosmological simulation of a system which grows at late times predominantly by minor mergers and accretion of stars. We can successfully apply simple scaling relations derived from the virial theorem to demonstrate that the size increase and decrease in density and velocity dispersion is a natural consequence of mass assembly by much less massive stellar systems and accretion (Cenarro & Trujillo 2009) and cannot be explained by mass assembly histories dominated by major stellar mergers.

In the simulation, a first phase ($6 > z > 2$) dominated by in situ star formation from inflowing cold gas (see, e.g., Dekel et al. 2009 and references therein) produces a massive and dense stellar system with sizes $r_{1/2} \leqslant 1$ kpc. This phase of the formation of the cores of ellipticals is followed by an extended phase ($3 > z > 0$) with little in situ star formation but significant accretion of stellar material. This material can be stripped at larger radii and increases the size of the system with time. At the same time the central concentration is reduced by dynamical friction from the surviving cores (see El-Zant et al. 2001). The apparent size increase is caused by the initial dominance of the in situ component being heated and, at larger radii, overshadowed ultimately by the accreted stars. From $z = 3$ to $z = 0$ the effective radius of the system increases by a factor of 3.5 with a decrease in the effective density of more than an order of magnitude and a decrease in velocity dispersion of 20%, in good agreement with predictions from simple scaling relations for the accretion of minor mergers.

Detailed investigations of dark matter simulations (see, e.g., Genel et al. 2008b; Fakhouri & Ma 2008; Genel et al. 2008a) as well as recent observations (see, e.g., Bundy et al. 2009) on the mass assembly mechanisms of early-type galaxies and their dark matter halos demonstrate the significance of minor mergers. In addition, due to the shape of the mass function, massive systems at high redshift are more likely to experience minor mergers, than lower mass galaxies. If the size evolution is in general driven by minor mergers we would expect a differential size increase, e.g., more massive high-redshift systems grow larger than lower mass systems. At the same time minor mergers do also play an important role for the gravitational heating of halo gas, thereby suppressing the formation of new stars (Johansson et al. 2009b).

A picture of a two-phase formation process for massive spheroidal galaxies has a number of virtues. In the first dissipative phase at high redshift stars form quickly and build the compact progenitor of present-day ellipticals. In fact, it seems of minor importance if the gas is funneled to the center through streams or mergers of extended gas dominated disks (see, e.g., Robertson et al. 2006; Johansson et al. 2009a; Dekel et al. 2009) as long as it happens on a short timescale. The stars formed at this early phase are expected to be significantly enriched in alpha-elements as expected from observations (Thomas et al. 2005) and form the compact core of the elliptical galaxy. Later on metal-poor stars from smaller systems are accreted and form the halo of the galaxy resulting in the observed metallicity gradient. This inside out formation scenario is also made plausible by recent observations of Bezanson et al. (2009). There is an important test of the picture presented in this Letter. If correct, then the outer parts of massive giant ellipticals will tend to be old, blue, metal-poor, and relatively uniform from galaxy to galaxy since they are all composed essentially of the debris from tidally destroyed accreted small systems.

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