Elliptical galaxies formed in a major merger have a tendency to become more nearly spherical with time, thanks to the gravitational effect of their central black hole (or black holes). Observational results indicate that elliptical galaxies with older stellar populations \((t > 7.5 \text{ Gyr})\) have rounder central isophotes than ellipticals with younger stellar populations. In addition, the older ellipticals tend to have core profiles, while the younger ellipticals have power-law profiles. Numerical simulations of galaxy mergers indicate that if one or both of the progenitors have a central black hole with mass \(\sim 0.2\%\) of the stellar mass, then the effect of the black hole(s) is to make the central regions of the remnant rounder, with a characteristic time scale of a few gigayears.

1 Analytic

In a hierarchical clustering scenario, elliptical galaxies form by the merger of smaller stellar systems. Mergers of equal-mass progenitors tend to form fairly flattened systems; after violent relaxation, the ratio of the shortest to longest axis of the merger remnant is typically \(c/a \sim 0.5\). However, once an elliptical merger remnant has completed violent relaxation, its shape does not remain constant. In the central regions of the galaxy – well inside the effective radius – the morphological evolution is driven by two-body relaxation, the result of close gravitational encounters between the point masses of which the galaxy is made. The net effect of two-body relaxation is to make a galaxy more nearly spherical with time.

Consider an idealized case of two-body relaxation in which a mass \(M\) is plunked down in an isothermal stellar system with velocity dispersion \(\sigma\). The introduced mass will disrupt the orbits of stars which come within a critical distance \(b \sim GM/\sigma^2\). If the mass \(M\) is just another star, with mass \(M \sim 1 \, \text{M}_\odot\), then stars will have to come within a distance \(b \sim 5 \, \text{R}_\odot \,(\sigma/200 \, \text{km s}^{-1})^{-2}\) before their orbits are randomized. Thus, for a typical elliptical galaxy, stars must come within a few stellar radii of each other for two-body relaxation to occur, and the star/star relaxation time is much longer than a Hubble time. If stars were the only point masses which elliptical galaxies contained, we would thus conclude that the effects of two-body relaxation on the structure of ellipticals are negligibly small so far. However, there’s more to a galaxy than stars. Most,
if not all, elliptical galaxies contain central black holes, with a mass given by the relation \( M_{\text{BH}} \approx 10^8 M_\odot (\sigma/200 \text{ km s}^{-1})^{4.8} \). With this black hole mass, a star coming within a distance \( b \sim 10 \text{ pc}(\sigma/200 \text{ km s}^{-1})^{2.8} \) will have its orbit disrupted. Thus, relaxation due to star/black-hole encounters will be vastly more effective than relaxation due to star/star encounters. The net effect of the central black hole will be to increase the entropy of the stellar system and to make it more nearly spherical with time.

It should also be noted that if an elliptical forms by the merger of two progenitors, each with a central black hole, a binary black hole may exist for many gigayears before dynamical friction, gas dynamical effects, and gravitational radiation will cause the two black holes to coalesce. Three-body interactions between a star and a bound black hole binary will generally increase the star’s kinetic energy. Thus, binary black holes have been proposed as a mechanism for lowering the stellar density in the central regions of an elliptical and creating a ‘core’ profile.\(^2\)

2 Observational

Given the brevity of human life, we cannot sit and watch for a few billion years while a post-merger elliptical becomes rounder with time; nor can we take the time to circumnavigate a galaxy and discover its true three-dimensional shape at a given time. The best we can do, to test our belief that merger remnants become rounder with time, is to examine a sample of elliptical galaxies and see whether the apparent shape of a galaxy is correlated with the time elapsed since it last underwent a major merger.

Estimating the time that has passed since an elliptical galaxy’s last major merger is not a simple or straightforward task. However, if the merger in question involved a pair of reasonably gas-rich galaxies, then the merger will be accompanied by a burst of star formation that will leave its spectroscopic mark on the galaxy. Terlevich and Forbes have recently compiled a catalog of spectroscopic galaxy ages, based on a homogeneous data set of galaxies with high-quality \( \text{H}\beta \) and \([\text{MgFe}]\) absorption line indices. The stellar population model of Worthey is used to assign an age to the stellar population of each galaxy in the catalog. For the 74 elliptical galaxies in the Terlevich & Forbes catalog, we searched the published literature for isophotal fits, and found the apparent axis ratio \( q \equiv b/a \) at six reference radii: \( R \equiv (ab)^{1/2} = R_e/16, R_e/8, R_e/4, R_e/2, R_e, \) and \( 2R_e \). Details of the analysis, for those who love details, are given by Ryden, Forbes, & Terlevich.\(^8\)

Figure 1 is a plot of \( q \) versus the spectroscopic age \( t \) at the six reference radii. Particularly at the innermost radius, \( R = R_e/16 \), there is a correlation
Figure 1: Isophotal axis ratio $q$ versus estimated age $t$ of the central stellar population. Axis ratios are measured at $R = R_e/16$, $R_e/8$, $R_e/4$, $R_e/2$, $R_e$, and $2R_e$. Galaxies with core profiles are indicated by squares, galaxies with power-law profiles are indicated by triangles, and galaxies with unknown profile type are indicated by open circles.
between $q$ and $t$, with ‘old’ ellipticals tending to be rounder than ‘young’ ellipticals. A Kolmogorov-Smirnov test, comparing the distribution of $q(R_e/6)$ for galaxies with $t \leq 7.5$ Gyr to the distribution for galaxies with $t > 7.5$ Gyr, reveals that the distributions differ significantly, with $P_{KS} = 0.00034$.

The question ‘Why are there so many round old ellipticals?’ is similar to the question ‘Why are there so many little old ladies?’ It is tempting to interpret the prevalence of little old ladies as being due purely to the evolution of individuals, with ladies tending to become littler as they grow older. However, there are other effects at work as well. For instance, extremely large ladies tend to die prematurely; in addition, today’s population of old ladies grew up when nutritional standards were lower, thus resulting in reduced adult stature. Both these effects, neither of which involves the morphological evolution of individual ladies, contribute to the predominance of little old ladies over large old ladies. Similarly, the predominance over round old ellipticals over flattened old ellipticals is not necessarily due to the morphological evolution of individual galaxies.

The difference in apparent shape between galaxies with young stellar populations and those with old stellar populations is tied, in a most intriguing manner, to the core/power-law distinction. Elliptical galaxies with power-law profiles have luminosity densities which are well fit by a pure power law all the way to the limit of resolution; ellipticals with core profiles, by contrast, have densities which show a break to a shallower inner slope. In Figure 1, core ellipticals are designated by squares, power-law ellipticals are designated by triangles, and ellipticals of unknown profile type are designated by empty circles.

Note that the ‘old’ ellipticals tend to have core profiles and round central isophotes, while the ‘young’ ellipticals tend to have power-law profiles and flattened central isophotes. The 29 known core galaxies in our sample have a mean and standard deviation for their estimated stellar ages of $t = 8.6 \pm 3.3$ Gyr; the 22 known power-law galaxies have $t = 6.9 \pm 3.5$ Gyr.

3 Numerical

The observational results are consistent with a scenario in which elliptical galaxies are formed in a major merger, then evolve to become more nearly spherical with time. However, they do not compel such a scenario – remember the cautionary tale of the little old ladies! Fortunately, numerical simulations of galaxy mergers, and of the evolution of merger remnants, can be run on timescales much shorter than a gigayear (and, more to the point, shorter than the lifetime of a graduate student.)

We ran n-body simulations (with no attempt to include gas dynamical
effects) of the merger of a pair of disk/bulge/halo galaxies. In our merger simulations, each progenitor has a disk:bulge:halo mass ratio of 1:1:5.8. (The progenitors can be thought of as a pair of S0 galaxies, with big bulges and no gas). The disk, the bulge, and the halo each contain 16K particles. We ran three different merger simulations, differing only in the mass of the central black hole assigned to each progenitor galaxy. One simulation contained no central black holes. In the next simulation, the progenitor galaxies contained central black holes equal in mass to 0.2% of the total stellar mass (disk + bulge). In the final simulation, the progenitors contained black holes equal in mass to 2% of the total stellar mass.

We used the n-body code GADGET\textsuperscript{10} for all integrations. GADGET is a tree code designed to run on distributed memory, multi-processor comput-
Figure 3: As in Figure 2, but for a simulation in which the merging progenitors have moderately massive central black holes (equal in mass to 0.2% of the total stellar mass).

It employs continuously variable timesteps which are individual to each particle. The timesteps are computed with an accuracy parameter, $\eta$, set to 0.02. The gravitational smoothing lengths for the disk, bulge, and halo particles were 0.08, 0.08, and 0.4 respectively. For force calculations between any particle and a black hole, a smoothing length of 0.001 was used. (For reference, the disk scale length of the progenitor galaxies was 1.0.)

In the first simulation, whose results are presented in Figure 2, the merging galaxies contained no central black holes. Note that both the intermediate-to-long axis ratio (illustrated in the upper panel of Figure 2) and the short-to-long axis ratio (illustrated in the lower panel) evolve steadily toward unity in this simulation, despite the absence of a central black hole. This is a spurious two-body relaxation effect, resulting from the coarseness of our simulation; instead of being made of tens of billions of stars, the 'luminous' portions of our simulated galaxies contain only tens of thousands of mass points.
Figure 4: As in Figure 2, but for a simulation in which the merging progenitors have extremely massive central black holes (equal in mass to 2% of the total stellar mass).

In Figure 3, showing the evolution in shape of a merger remnant with moderate mass black holes (0.2% of the total stellar mass of the progenitors), we see that the evolution toward a spherical shape is more rapid than in the absence of black holes. Moreover, the drive toward a spherical shape is most rapid for the 5% most tightly bound particles (the heavy solid line in Figure 3) than for the 50% most tightly bound (the light solid line). In short, the added black holes drive the central, most tightly bound, regions of the merger remnant toward a spherical shape on gigayear timescales.

Adding black holes an order of magnitude more massive, as shown in Figure 4, dramatically shortens the time for making the merger remnant spherical. With big black holes, equal to 2% of the total stellar mass, the merger remnant rapidly becomes very nearly oblate (that is, the ratio $b/a$, shown in the upper panel of Figure 4, rapidly approaches one.) The ratio $c/a$, shown in the lower panel, approaches unity more gradually. However, we can conclude that if
merging galaxies contained extremely massive black holes, equal to one or two percent of their total stellar mass, then merger remnants would become nearly oblate on timescales shorter than a gigayear. The relative scarcity of nearly circular isophotes ($q > 0.95$) in the central regions of elliptical galaxies – see the upper left panel of Figure 1 – argues that elliptical galaxies are probably not oblate in their central regions. However, given the relatively small size of the Terlevich-Forbes sample, this is not a chiseled-in-stone conclusion.

More data are needed (unsurprisingly). A larger sample size of observational data will help to pin down the relationship among galaxy age, isophote shape, and luminosity profile type. Much work remains to be done (also unsurprisingly). Higher-resolution numerical simulations will reduce the ugly effects of spurious two-body relaxation and will enable us to focus on the physically real effects of massive black holes.

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