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MAJOR MERGING: THE WAY TO MAKE A MASSIVE, PASSIVE GALAXY

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ABSTRACT

We analyze the projected axial ratio distribution, $p(b/a)$, of galaxies that were spectroscopically selected from the Sloan Digital Sky Survey (DR6) to have low star formation rates. For these quiescent galaxies we find a rather abrupt change in $p(b/a)$ at a stellar mass of $\sim 10^{11}\ M_\odot$: at higher masses there are hardly any galaxies with $b/a < 0.6$, implying that essentially none of them have disk-like intrinsic shapes and must be spheroidal. This transition mass is ∼3–4 times higher than the threshold mass above which quiescent galaxies dominate in number over star-forming galaxies, which suggests that these mass scales are unrelated. At masses lower than $\sim 10^{11}\ M_\odot$, quiescent galaxies show a large range in axial ratios, implying a mix of bulge- and disk-dominated galaxies. Our result strongly suggests that major merging is the most important, and perhaps only relevant, evolutionary channel to produce massive ($> 10^{11}\ M_\odot$), quiescent galaxies, as it inevitably results in spheroids.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: fundamental parameters – galaxies: statistics – galaxies: structure

1. INTRODUCTION

Even galaxies with little star formation activity continue to evolve, as evidenced by the substantial increase of their cosmic stellar mass density over the past 7 billion years (Bell et al. 2004; Faber et al. 2007; Brown et al. 2007). This must be related to the decreasing star formation activity over the same period (e.g., Le Floc'h et al. 2005), and the production of such quiescent galaxies through the truncation of star formation (e.g., Faber et al. 2007; Bell et al. 2007); the color scatter among quiescent galaxies and its evolution are in precise agreement with such a scenario (Ruhland et al. 2009). There are, however, quiescent galaxies at all redshifts $z \lesssim 1.3$ that are more massive than the most massive star-forming galaxies. This implies that star formation in the most massive galaxies was truncated even earlier, and/or that mergers play an important role in producing massive galaxies.

Evidence for the early formation of massive galaxies is provided by their old stellar populations. However, we need to bear in mind that there can be a large difference between the age of the stellar population and the assembly age, especially if mergers are important, as is the case in a hierarchical framework for galaxy formation (De Lucia et al. 2007). Hence, the number density evolution of galaxies is important in constraining their assembly history. Measuring this is difficult because of its sensitivity to the luminosity evolution correction, especially for massive galaxies at the exponential cut-off of the mass function. As a result, there is no consensus among the currently available measurements (Cimatti et al. 2006; Wake et al. 2006; Brown et al. 2007; Cool et al. 2008).

Given these difficulties, other observations have been used to either directly or indirectly constrain the assembly of galaxies. Merging activity among the massive galaxy population is observed (e.g., van Dokkum et al. 1999; van Dokkum 2005; Bell et al. 2006a, 2006b; Lin et al. 2008), and has been shown to produce a color–magnitude relation that is in agreement with observations (Skelton et al. 2009). However, its cosmological relevance has always been difficult to determine, given the uncertainties in converting observed merger fractions to merger rates and the associated growth in mass. An independent and indirect indication that massive galaxies undergo continuous evolution is provided by the recent result that high-redshift quiescent galaxies are substantially smaller than local galaxies with the same mass (see van der Wel et al. 2008, and references therein). This strongly suggests that mergers are important (see, e.g., van der Wel et al. 2009), and that the assembly of massive galaxies is continuing up until the present day. Another indirect, yet powerful, constraint is provided by the evolution in the clustering and halo occupation distribution of red galaxies (White et al. 2007; Conroy et al. 2007; Brown et al. 2008): the evolution in the clustering strength of red galaxies is slower than expected in the absence of merging.

In this Letter we address the question whether major merging is the dominant mechanism for the production of very massive, quiescent galaxies. The argument that we invoke is simply that major merging generally leads to rounder galaxies. An analysis of the shape distribution of quiescent galaxies can therefore constrain the importance of merging. Since merging among galaxies with mass ratios of $\lesssim 3$ is the only known mechanism to produce round galaxies (see Section 3 for further discussion), this is a powerful test. The disadvantage of this method, compared to those mentioned above, is that no information about the timescale and epoch of galaxy assembly can be inferred.

Vincent & Ryden (2005) and Padilla & Strauss (2008) were the first to systematically study the axial ratio distribution, $p(b/a)$, of a large number of galaxies, selected from the Sloan Digital Sky Survey (SDSS). Through a detailed analysis, they infer the intrinsic shape distribution and the effect of extinction. Both divide the sample into "elliptical" and "spiral" galaxies, and confirmed that luminous "elliptical" galaxies are, on average, rounder and tri-axial, compared to low-luminosity "ellipticals," which are more elongated and oblate (Davies et al. 1983; Franx et al. 1991), and display disky isophotes (Jørgensen & Franx 1994). This phenomenon is not recent: Holden et al. (2009) showed that this trend persists at least out to $z \sim 1$. Here we present a complementary, modified analysis, focusing on $p(b/a)$ as a function of stellar mass for quiescent, i.e., non-star-forming, galaxies. Because mass-to-light ratios are

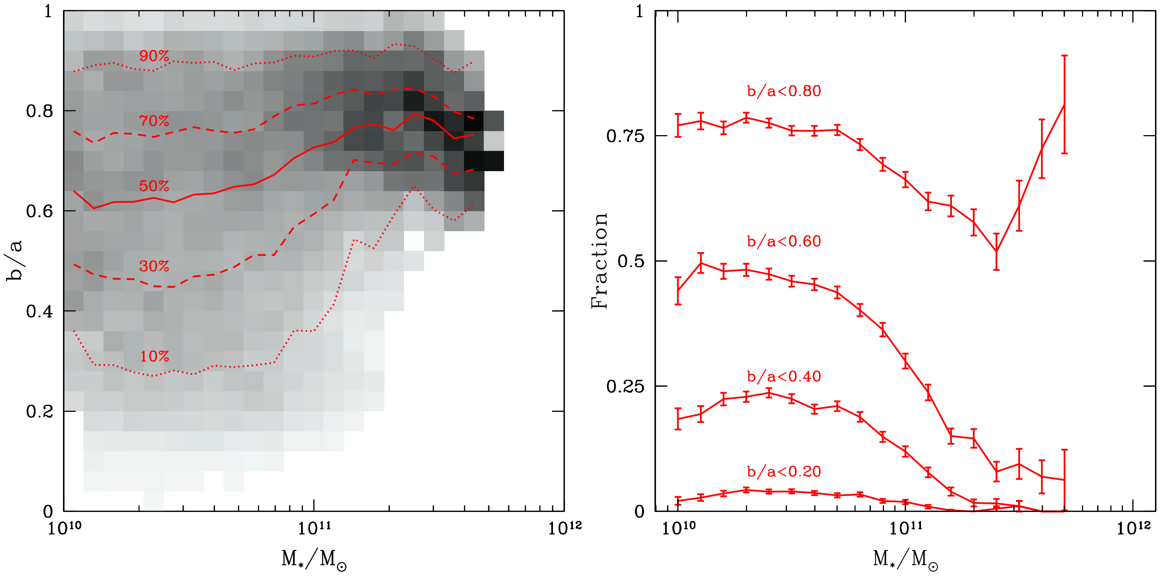

Figure 1. Left: axial ratio distribution, $p(b/a)$, as a function of stellar mass for spectroscopically selected quiescent galaxies from the SDSS at $0.04 < z < 0.08$. The gray scale represents, normalized to the total number of galaxies in narrow bins of stellar mass, the fraction of galaxies with axial ratio b/a. The upper boundaries below which, as a function of mass, 10%, 30%, 50%, 70%, and 90% of galaxies are located, are delineated by the red lines. Right: fraction of galaxies with axial ratios b/a smaller than 0.8, 0.6, 0.4, and 0.2, as a function of stellar mass. These figures clearly show that at $M_* \geqslant 10^{11}\ M_\odot$, the fraction of galaxies with small b/a decreases rapidly with mass. At lower masses, $p(b/a)$ is approximately uniform in the range $0.3 < b/a < 0.9$, implying a significant contribution of disks. At higher masses, axial ratios are approximately evenly distributed in the range $0.6 < b/a < 0.9$, which shows that disks must be rare, and galaxies intrinsically round.

well constrained by broadband colors for quiescent galaxies, stellar mass estimates are robust. This is essential for our purposes, as we are interested in the most massive objects, i.e., those that populate the exponential tail of the mass function. Furthermore, as opposed to previous studies, we pre-select galaxies independent of their photometric properties. Our shape-independent, spectroscopic selection criteria circumvent the biases that are potentially introduced by selecting galaxies by their "morphological" properties, or some pre-defined surface brightness profile.

With this sample, for which we have determined axial ratios from our own fits to two-dimensional light distributions, we address the following specific questions. Are high-mass, quiescent galaxies rounder than low-mass quiescent galaxies? If so, is there a mass limit at which $p(b/a)$ distinctly changes, and above which disk-dominated are completely absent? Such evidence would imply that the only evolutionary path to such masses is a disk-destroying mechanism, i.e., major merging.

2. THE SAMPLE

We select a sample of 17,480 quiescent galaxies from Data Release 6 of the SDSS (Adelman-McCarthy 2008). Our sample includes galaxies at redshifts $0.04 < z < 0.08$ without detectable [O II] and Hα emission lines. The selection criteria are described and motivated in full by Graves et al. (2009); but as opposed to that work, we do not exclude galaxies with a low concentration index and galaxies that are fit better by an exponential profile than by a de Vaucouleurs (1948) profile, because this may exclude quiescent, yet disk-like galaxies, which are obviously relevant for quantifying $p(b/a)$ of quiescent galaxies. As a consequence, our sample may include galaxies with star formation in an extended disk outside the SDSS spectroscopic fiber. This effect, however, does not affect our main conclusion that quiescent massive galaxies with prominent disks are extremely rare (see Section 3). Rather, such a bias works in the opposite direction in the sense that it would lead to the mistaken inclusion of galaxies with large disks.

The exclusion of all galaxies with emission lines also excludes quiescent galaxies with active galactic nuclei. Their number, however, is small, and make up a small fraction of the population (e.g., Pasquali et al. 2009) that is negligible for our purposes.

The axial ratios were obtained as described by van der Wel et al. (2008). Briefly, GALFIT (Peng et al. 2002) is used to determine from the r-band the radii, axial ratios, position angles, and total magnitudes, assuming a de Vaucouleurs (1948) surface brightness profile. We have verified that adopting surface brightness models with a free Sérsic index does not lead to a significantly different $p(b/a)$.

The stellar masses are derived with the simple conversion from color to mass-to-light ratio (Bell et al. 2003), but are normalized to correspond to the Kroupa (2001) stellar initial mass function. The assumed cosmology is $(\Omega_{\rm M}, \Omega_\Lambda, h) = (0.3, 0.7, 0.7)$.

The sample is complete over the entire redshift range $0.04 < z < 0.08$ down to $M_* \sim 4 \times 10^{10}\ M_\odot$, set by the spectroscopic magnitude limit of the SDSS ($r = 17.7$). The SDSS may be incomplete for low-luminosity, low-surface brightness galaxies (Blanton et al. 2005), which could, in addition, depend on their orientation (see, e.g., Odewahn et al. 1997). However, since we are concerned with the high-mass end of the galaxy population, this does not play a role. Moreover, simulations of images with even lower signal-to-ratio than those of the massive galaxies analyzed here demonstrate that axial ratio measurements from GALFIT are robust and accurate (Holden et al. 2009). In summary, the lack of galaxies with small b/a, reported in the following section, is not in any way compromised by selection effects or measurement errors.

3. RESULTS AND DISCUSSION

In Figure 1(a) we show $p(b/a)$ of the 17,480 spectroscopically selected, quiescent galaxies as a function of stellar mass. $p(b/a)$ is shown in gray scale, with the percentiles of the cumulative b/a distribution shown as (red) lines. Figure 1(a) immediately demonstrates that for quiescent galaxies, the projected axial ratio distribution is a strong function of stellar mass. In the narrow mass range $8 \times 10^{10} \lesssim M_*/M_\odot \lesssim 2 \times 10^{11}$ there is a rapid decrease in the number of galaxies with small axial ratios. As further illustrated by Figure 1(b), above $M_* \sim 2 \times 10^{11}\ M_\odot$ quiescent galaxies with $b/a < 0.6$ are essentially absent.

This result shows that evolutionary paths that lead to quiescent galaxies with stellar mass $M_* \gtrsim 2 \times 10^{11}\ M_\odot$ all but exclude the existence, or the survival, of highly flattened, disk-like stellar components. As highly flattened stellar systems are quite common at lower masses, in the possible realm of plausible progenitors of high-mass galaxies, this result implies the destruction of the flattened component in whatever process causes growth beyond $M_* \sim 2 \times 10^{11}\ M_\odot$. Therefore, our result that essentially all quiescent galaxies with masses larger than $M_* \sim 2 \times 10^{11}\ M_\odot$ are round strongly suggests that for such galaxies major mergers are the dominant, perhaps even unique, formation channel. The destruction of a stellar disk requires a major merger, i.e., a merger involving progenitors with a relatively small mass ratio of at most ∼3, mergers with a larger mass ratio leaving stellar disks intact (see, e.g., Bekki 1998; Bournaud et al. 2004). Moreover, most likely, the progenitors are not very gas rich, as this would produce a disky remnant (e.g., Naab et al. 2006).

It has been suggested that cold flows are responsible for the formation of massive, classical bulges at high redshift (Dekel et al. 2009; Ceverino et al. 2009). In this scenario, intensely star-forming "knots" merge, forming a massive bulge (see also Noguchi 1999). However, a substantial fraction of the mass (∼50%) is still predicted to reside in a disk. Even at later stages, when the gas disk has become stable against fragmentation and collapse ("morphological quenching"; Martig et al. 2009), the stellar disk remains intact and contains a non-negligible fraction of the total mass. In short, although cold flows plausibly produce quiescent galaxies, the end-products will not be uniquely round. Only in the case of sufficient merger activity would galaxies become spheroidal.

In passing, we note that the sharp decrease in the fraction of very round galaxies ($b/a > 0.8$) at the very highest masses ($M > 3 \times 10^{11}\ M_\odot$) signifies that such high mass galaxies are typically brightest group/cluster galaxies, which tend to be slightly more elongated than "normal" massive elliptical galaxies (see Bernardi et al. 2008).

As already noted above, at masses lower than $M_* \sim 10^{11}\ M_\odot$, quiescent galaxies display a large range in axial ratios, which implies that star formation truncation mechanisms below $10^{11}\ M_\odot$ are often not associated with the destruction of the disk. It remains to be tested whether $p(b/a)$ of low-mass quiescent galaxies is similar to or different from $p(b/a)$ of star-forming galaxies in the same mass range. Such an analysis, which is non-trivial because of the effects of extinction and color gradients, will constrain the degree to which mergers or bulge growth regulate star formation at these lower masses.

Another open question concerns the number and properties of massive, star-forming galaxies. Morphological studies suggest that a large fraction (20%–40%) of all galaxies more massive than $M \sim 10^{11}\ M_\odot$ are late-type galaxies (van der Wel 2008; Bamford et al. 2009), and their high masses of at least some of these objects are confirmed by their rotational velocities (e.g., Courteau et al. 2007). Yet, the degree to which such galaxies are disk-dominated and should be considered actively star forming remains to be determined. It would, therefore, be premature to conclude that merging is the only way to produce a massive galaxy in general, and therefore restrict this proposition to the formation of massive, quiescent galaxies.

The picture sketched by the axial ratio distribution of quiescent galaxies is in agreement with the strong correlation between structure and mass for galaxies in general (e.g., Kauffmann et al. 2003; van der Wel 2008) and early-type galaxies in particular (e.g., Caon et al. 1993; Graham & Guzmán 2003): high-mass galaxies are more concentrated and have higher Sérsic indices than low-mass galaxies. These trends are an indirect indication of a decreasing importance of disks for galaxies with higher masses, although part of this trend is caused by the increase in Sérsic index with galaxy mass among spheroidal galaxies. In our sample we see a similar trend: in the mass range $10^{10} < M_*/M_\odot < 2 \times 10^{10}$, 41% of the galaxies have Sérsic indices $n < 3$, whereas at higher masses, $M_* > 2 \times 10^{11}\ M_\odot$, only 3% have such low Sérsic indices. We postpone a full exploration of the joint behavior of shape and structure as a function of galaxy mass until a future paper, but it is encouraging that the apparent absence of prominent disks in high-mass, quiescent galaxies is reflected in both the Sérsic index and $p(b/a)$.

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