INTRINSIC AXIS RATIO DISTRIBUTION OF EARLY-TYPE GALAXIES FROM THE SLOAN DIGITAL SKY SURVEY

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Abstract
Using the Sloan Digital Sky Survey Data Release 5, we have investigated the intrinsic axis ratio distribution (ARD) for early-type galaxies. We have constructed a volume-limited sample of 3922 visually inspected early-type galaxies at 0.05 ≤ z ≤ 0.06, carefully considering sampling biases caused by the galaxy isophotal size and luminosity. We attempt to deproject the observed ARD into three-dimensional types (oblate, prolate, and triaxial), which are classified in terms of triaxiality. We confirm that no linear combination of randomly distributed axis ratios of the three types can reproduce the observed ARD. However, using Gaussian intrinsic distributions, we have found reasonable fits to the data using preferred mean axis ratios for the oblate, prolate, and triaxial (triaxials are given in two axis ratios) types of μo = 0.44, μp = 0.72, μt,β = 0.92, and μt,γ = 0.78, where the fractions of oblate, prolate, and triaxial types are O:P:T = 0.29 ± 0.09:0.26 ± 0.11:0.45 ± 0.13. We have also found that the luminous sample (−23.3 < M_r ≤ −21.2) tends to have more triaxial types than the less luminous (−21.2 < M_r < −19.3) sample does. Oblate types are relatively more abundant among the less luminous galaxies. Interestingly, the preferences of axis ratios for triaxial types in the two luminosity classes are remarkably similar. We have not found any significant influence of the local galaxy number density on the ARD. We show that the results can be seriously affected by the details of the data selection and type classification scheme. Caveats and implications for galaxy formation are discussed.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: kinematics and dynamics — methods: statistical — surveys

1. INTRODUCTION

Ever since Hubble (1926) investigated the apparent flattenings of early-type galaxies, numerous studies have attempted to pin down their intrinsic shapes. Such efforts mainly focused on the apparent axis ratio, not only because it is easy to measure, but also because its distribution can be used to extract the kinematics of galaxies and may even constrain their general formation history.

Early studies using the apparent axis ratio distribution (ARD) were made under the assumption that early-type galaxies are composed of one type. Assuming oblateness alone, Sandage et al. (1970) suggested the possibility of a Gaussian or skewed binomial distribution of intrinsic ARDs using the Reference Catalog of Bright Galaxies (RC1; de Vaucouleurs & de Vaucouleurs 1964). The approach of Binney (1978), which assumed prolateness, also successfully reproduced the apparent ARD from RC1. The existence of triaxial galaxies (Bertola & Capaccioli 1975; Illingworth 1977) opened up a better chance to reproduce the observed ARD. Binggeli (1980) and Benacchio & Galleta (1980) showed that the apparent ARDs for 160 elliptical galaxies from the Revised Shapley-Ames catalog of bright galaxies (Sandage & Tammann 1981) and 348 elliptical galaxies from Strom & Strom (1978a, 1978b, 1978c) were well represented as a group of triaxial galaxies, assuming a fixed case of β = (1 + γ)/2, where β is the ratio between the second longest axis and the longest axis and γ is the ratio of the shortest axis to the longest axis. In particular, Binney & de Vaucouleurs (1981) aimed to reconstruct the apparent ARD for RC2 (de Vaucouleurs et al. 1976) using Lucy’s inversion technique (Lucy 1974; see also Noerdlinger 1979). They considered oblate, prolate, and triaxial types (O, P, and T) separately and still found acceptable fits to the observed ARD. The limitation of this technique, however, is that it is difficult to constrain the ratios between the O, P, and T galaxies.

More recently, Fasano & Vio (1991) concluded that a purely biaxial model cannot reproduce the small number of apparently round galaxies. This paucity, however, looks significantly different when samples are drawn from different catalogs (e.g., RC1, RC2, or the Revised Shapley-Ames Catalog of Galaxies). This obviously results in disparate intrinsic distributions. Furthermore, Lambas et al. (1992) found a reasonable fit to the sample of 2135 galaxies from the APM Galaxy Survey (Maddox et al. 1990) by assuming that all elliptical galaxies are triaxial whose intrinsic distributions are two-dimensional Gaussians. The similar work done by Ryden (1992) presents consistent results. These results support the assertion that the paucity of round galaxies can be reproduced by a dominantly triaxial galaxy population. In light of its usefulness, it is important to accurately sample the observed ARD.

Fortunately, Sloan Digital Sky Survey (SDSS) data (Adelman-McCarthy et al. 2006) allow us to study the apparent flattenings for a large number of galaxies. Our effort to make a complete volume-limited sample is one of the main factors distinguishing our work from previous studies.

We also note the interesting result of Davies et al. (1983), who found that bright elliptical galaxies may be rotating more slowly than faint ones. Tremblay & Merritt (1996) found that the apparent ARD is markedly different for two luminosity classes; the elliptical galaxies that are brighter than M_B ≈ −20 are rounder than the less luminous ones. In particular, recent observations show that the division clearly occurs at M_B = −20.5 (Rest & van den Bosch 2001), and they also support previous works that suggested that bright galaxies show a core profile and boxy isophotes, whereas faint galaxies have a power-law profile and disky isophotes (Bender 1988; Kormendy & Bender 1996; Faber et al. 1997). Therefore, we investigate the effect of the galaxy luminosity on the ARD.

Another factor we should note regarding the intrinsic shape of early-type galaxies is an environmental dependence. Dressler (1980) pointed out a density-morphology relation that reflects the
importance on the formation process. We thus search for the connection between the intrinsic shape and the environment for early types.

In this paper, we propose two simplifying assumptions: (1) early-type galaxies are geometrically perfect ellipsoids, and (2) they are randomly oriented. We assume that early types consist of oblate, prolate, and triaxial types. We believe that this assumption makes our approach more realistic than the previous models that were composed of only one or of limited types. On this basis, we investigate the projection effect on the apparent ARD. We introduce our sample selection with completeness tests in § 3. In § 4, we investigate the intrinsic ARD for volume-limited samples. In § 5, we analyze the intrinsic shape of two different luminosity samples. Dependence of the ARD on the environment is investigated in § 6. In § 7, we discuss the limitations of our approach. Finally, we discuss our results and their implications in § 8.

2. ANALYTIC APPARENT AXIS RATIO DISTRIBUTION

We use an analytical description to calculate the probability distribution (Franx et al. 1991; Binney & Merrifield 1998, p. 194). The probability of finding the apparent ellipticity (ε) in the interval (ε, ε + dε) is

\[
p(\epsilon) \ d\epsilon = \frac{(1 - e)\sqrt{e}}{\pi} \int_{\mu_2}^{\mu_1} \frac{\mu^2}{\sqrt{1-h(\mu)b(\epsilon)}} \ d\mu \ d\epsilon \quad \text{for } 0 \leq \epsilon \leq \epsilon_1,
\]

\[
= \frac{\mu_1^2}{\sqrt{1-h(\mu)b(\epsilon)}} \quad \text{for } \epsilon_1 \leq \epsilon \leq 1,
\]

where \( e = (1 - \epsilon)^2 \), \( h(\tau) = (\tau - a^2)(\tau - b^2)(\tau - c^2) \), and \( \epsilon_1 = 1 - c/a \). The quantities \( a, b, \) and \( c \) indicate the lengths of the three axes of an ellipsoid, respectively. For galaxies with \( b/a > c/b \) (oblate triaxial), the conical coordinates \( \mu_1 \) and \( \mu_2 \), which depend on the galaxy shape, are

\[
(\mu_1, \mu_2) = \begin{cases} (b^2, b^2/e) & \text{for } 0 \leq \epsilon \leq \epsilon_2, \\ (b^2, a^2) & \text{for } \epsilon_2 < \epsilon \leq \epsilon_3, \\ (c^2/e, a^2) & \text{for } \epsilon_3 < \epsilon \leq \epsilon_1, \end{cases}
\]

where \( \epsilon_2 = 1 - b/a \) and \( \epsilon_3 = 1 - c/b \). For galaxies with \( b/a \leq c/b \) (prolate triaxial), \( \mu_1 \) and \( \mu_2 \) can be written as

\[
(\mu_1, \mu_2) = \begin{cases} (b^2, b^2/e) & \text{for } 0 \leq \epsilon \leq \epsilon_3, \\ (c^2/e, b^2/e) & \text{for } \epsilon_3 < \epsilon \leq \epsilon_2, \\ (c^2/e, a^2) & \text{for } \epsilon_2 < \epsilon \leq \epsilon_1. \end{cases}
\]

In order to illustrate the type (OPT) dependence of the apparent ARD, we adopt the classification scheme of Franx et al. (1991). To classify the early-type systems, we use triaxiality (\( T \)),

\[
T = \frac{1 - \beta^2}{1 - \gamma^2},
\]

and each type can be expressed as follows:

- oblate: \( 0 \leq T < 0.25 \),
- triaxial: \( 0.25 \leq T < 0.75 \),
- prolate: \( 0.75 \leq T \leq 1.0 \).

In this study, we assume that there are no early-type galaxies with axis ratios smaller than 0.2, because such systems are rarely observed. In Figure 1 we display the classification scheme. Figure 2 shows the simplest special case of the apparent ARD, which is based on uniformly distributed intrinsic axis ratios, where by “uniformly distributed” we mean that there are no preferred values of the intrinsic ratios. The numbers of the samples of the three (O, P, and T) types simulated are normalized to be the same; hence, they are unbiased by the area difference between the types in Figure 1. If an observed ARD has a large number of round galaxies with values near 1, we can deduce that the oblate type is the main component, for example.

3. SDSS SAMPLE SELECTION AND DATA ANALYSIS

The SDSS provides a large homogeneous database. There are approximately 28,000 galaxies within 0.05 ≤ z ≤ 0.06, which constitutes an excellent sample for studying the ARD statistically.
In this section, we describe our data selection scheme and completeness tests.

3.1. Morphological Classification

A well-defined criterion for morphological classification is necessary in order to study the ARD of early-type galaxies. Because visual inspection of all galaxies is extremely time-consuming and still subjective, we adopted the SDSS pipeline parameter "fracDeV," which indicates the fraction of the brightness profile that can be explained by the de Vaucouleurs profile (de Vaucouleurs 1948) as follows:

\[ f_{\text{composite}} = \text{fracDeV} f_{\text{dev}} + (1 - \text{fracDeV}) f_{\text{exp}}, \]

where \( f_{\text{dev}} \) indicates de Vaucouleurs fluxes. We assume that a conservative sample of early-type galaxies have \( \text{fracDeV} \geq 0.95 \) in all three bands, \( g, r', \) and \( i' \), following the practice of Yi et al. (2005). Using this fracDeV parameter, we compile 4994 galaxies within \( 0.05 \leq z \leq 0.06 \).

3.2. Data Analysis

3.2.1. Luminosity Dependence

A complete volume-limited sample is crucial for this study because it has a direct effect on the intrinsic shapes of galaxies. But SDSS provides spectroscopic information only for the galaxies of \( r < 17.77 \); hence, our sample cannot be free from luminosity bias. To investigate this, we need to know how the ARD varies with the size of the major axis. Figure 3 shows the trend that the luminosity gradually increases with increasing minor axis for a fixed major-axis size. This effect is clearer for the larger galaxies because it has a direct effect on the intrinsic shapes of galaxies.

The ARD for the final sample is shown in Figure 4. For the purpose of comparison, we also plot the apparent ARD from the APM Bright Galaxy Catalogue (APMBGC) data (Loveday 1996). We bin the data by the size roughly drawn from the Izenman (1991) method, \( 0.68 \text{IQR} n^{-1/3} \), which is based on the total number \( n \) and the interquartile range (IQR), where \( 2.0 \leq a \leq 2.5 \) (Izenman 1991). The peak around \( p = 0.8 \) is noteworthy.
4. INTRINSIC AXIS RATIO DISTRIBUTION FOR VOLUME-LIMITED SAMPLE

It was demonstrated in Figure 2 that the apparent ARD is not uniform even though the intrinsic distribution is uniform. To extract the intrinsic shapes of our galaxies, we use composite models of the O, P, and T types that are based on the Franx et al. (1991) classification scheme (Fig. 1). In this section, we compare the observation with model distributions using two strategies.

4.1. Uniform Distribution of Intrinsic Axis Ratio

We investigate the possibility of a uniform intrinsic distribution. To measure the goodness of the fit, we use the reduced \( \chi^2 \), and this is constructed by considering the Poisson error. Using the volume-limited sample from §3, we try to derive the fractions of the O, P, and T types in the combination that best reproduces the observed ARD. We can express this with the weight \((W)\) of each type:

\[
\Phi_o W_o + \Phi_p W_p + \Phi_t W_t = \Phi_{\text{obs}},
\]

where the apparent ARD

\[
\Phi_i = \sum_\beta \sum_\gamma \Psi_i(\beta, \gamma).
\]

The index \(i\) indicates each type, and \(\Psi\) is the apparent ARD for a certain axis ratio \((\beta, \gamma)\). The weight directly reflects the frequency of each type. The best solution that results in a minimum \(\chi^2\) is \(W_o:W_p:W_t = 0.09:0.00:0.91\), but for a very poor statistic (\(\chi^2_{\text{red}} \sim 50\)). Hence, no linear combination of the O, P, and T types with a random ARD reproduces the observed ARD of our sample.

4.2. Gaussian Distribution of Intrinsic Axis Ratio

Since the random intrinsic ARD fails to reproduce the observed data, we adopt a Gaussian distribution. Although previous studies, which allowed arbitrary distribution, could estimate the preference of the axis ratio, it is nearly impossible to quantify the fraction of the oblate, prolate, and triaxial types. In this respect, a Gaussian is the best distribution with which to test the fraction and preference of the axis ratios. The Gaussian distribution can be written as

\[
F_{\text{Gau}}(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi} \sigma} \exp \left[-\frac{(x-\mu)^2}{2\sigma^2}\right],
\]

where \(\mu\) and \(\sigma\) correspond to the mean position and width, respectively, of the Gaussian distribution. Then preferences for oblate and prolate galaxies can be expressed as

\[
\Phi_o = \sum_\beta \sum_\gamma F_{\text{Gau}}(\gamma; \mu_o, \sigma_o) \Psi_o(\beta, \gamma),
\]

\[
\Phi_p = \sum_\beta \sum_\gamma F_{\text{Gau}}(\beta; \mu_p, \sigma_p) \Psi_p(\beta, \gamma).
\]

For triaxial galaxies, we use two Gaussian weights, following the Lambas et al. (1992) approach:

\[
\Phi_t = \sum_\beta \sum_\gamma F_{\text{Gau}}(\beta; \mu_t, \sigma_t) F_{\text{Gau}}(\gamma; \mu_t, \gamma) \Psi_t(\beta, \gamma)
\]

for \((\beta, \gamma) \leq T_{f,\text{min}} \leq (1-\beta^2)/(1-\gamma^2) < T_{f,\text{max}}\), where \(0.2 \leq \gamma \leq \beta \leq 1.0\).

To reproduce the observed ARD above, we imposed specific intrinsic axis ratios and sum over three probability distributions after multiplying their weight factors. We should note that these weight factors are different from the Gaussian weights in equation (6) and recall that this provides a simple framework in which we can investigate the fraction of each type.

With this approach we find good matches. The best-fit model that yields a minimum \(\chi^2 \approx 1\) is \((\mu_o, \mu_p, \mu_t, \sigma_o, \sigma_p, \sigma_t) = (0.46, 0.72, 0.92, 0.74)\) and \((\sigma_{\alpha}, \sigma_{\beta}, \sigma_{\gamma}) = (0.1, 0.05, 0.1, 0.3)\). For this case, we found that the fraction of each type is \(O:P:T = 0.35:0.18:0.47\). However, our parameter space is so complicated that the minimum \(\chi^2\) model may not represent the most meaningful result. Instead, the statistical properties of all possible models with reduced \(\chi^2\) values within the 1 \(\sigma\) range (\(\Delta \chi^2 < 1\)) are more meaningful because they all show good agreements with the observations (Fig. 5). Our results show that the triaxial component is dominant around the high axis ratio, while the oblate component also plays an important role in the low axis ratio region. Statistically, the total fraction of each type is \(O:P:T = 0.29 \pm 0.09:0.26 \pm 0.11:0.45 \pm 0.13\) in the 1 \(\sigma\) range, which suggests that triaxial early types are most common. For comparison to the “best-fit model,” the \(\chi^2\) space of the “good models” (\(\Delta \chi^2 < 1\)) shows a convergence at a slightly different configuration, \((\mu_o, \mu_p, \mu_t, \sigma_o, \sigma_p, \sigma_t) = (0.44, 0.72, 0.92, 0.78)\), as shown in Figure 6. We believe that this is a more statistically representative result.

In the similar simulation of Lambas et al. (1992), the optimal solution for fitting the apparent ARD from APMBGC data with a two-dimensional Gaussian had \(\mu_o = 0.95, \mu_t = 0.55, \sigma_o = 0.35, \sigma_p = 0.2\). Likely reasons for the difference between their results and ours are that (1) they considered only the triaxial type and used a different classification scheme and (2) the observed ARDs are slightly different. They used smaller values of \(\mu_t\) (i.e., flatter) than ours, probably in order to fit the low
axis ratio regions without considering the oblate and prolate elements. On the other hand, the results of Ryden (1992) that produce the best-fit model with $\mu_{\ell,0} = 0.98$, $\mu_{p,0} = 0.69$, and $\sigma_{t} = 0.11$ are closer to our results, but since their observed ARD was suppressed in the low axis ratio region, their best-fit triaxials were rounder than those in the Lambas et al. fit.

5. INTRINSIC AXIS RATIO DISTRIBUTION FOR DIFFERENT LUMINOSITIES

We investigate whether the two luminosity classes mentioned in §1 (Bender 1988; Kormendy & Bender 1996) have different intrinsic shapes by comparing their best-fit (within 1 $\sigma$) model OPT ratios. First, we divide galaxies into “luminous” ($M_r \leq -21.2$) and “less luminous” ($M_r > -21.2$) groups. Rest & van den Bosch (2001) found a division at $M_B \sim -20$, which corresponds to $M_r \sim -21.2$, using the transformation of Smith et al. (2002) and the typical color for early types ($B - V \sim 0.9$). As seen in Figure 7, the “luminous” sample exhibits a larger number of round galaxies. We derive the weight and preference of the intrinsic axis ratios for each type.

We first focus on the weight of each type between the two groups. Averaged over the region of the 1 $\sigma$ range ($\Delta \chi^2 \leq 1$), the O, P, and T weights for the luminous and less luminous samples are as follows:

- Luminous: $O : P : T = 0.13 \pm 0.08 : 0.20 \pm 0.13 : 0.67 \pm 0.13$
- Less luminous: $O : P : T = 0.38 \pm 0.08 : 0.18 \pm 0.10 : 0.43 \pm 0.11$

This implies that luminous early types are likely triaxial, whereas there are many oblate galaxies in the less luminous sample. We display in Figure 8 how each type can be viewed in the sky. Note that the galaxies with a high apparent axis ratio are likely triaxial regardless of their luminosity, and oblate galaxies are more common in the less luminous sample. This may indicate different formation processes between the two samples. We will discuss this in greater detail in §8. The dichotomy, if real, might be explained by the argument presented by Valluri & Merritt (1998) involving the central supermassive black hole and the crossing time difference between the bright and faint elliptical galaxies.

However, regarding preferences of the intrinsic axis ratio ($\mu$) and Gaussian widths ($\sigma$), there is no clear disparity between the two samples. The luminous sample shows a preference for $\mu_{\ell,0} = 0.90$, $\mu_{p,0} = 0.70$, and $\mu_{t} = 0.75$, while $\mu_{t}$ cannot be constrained because of the minimal contribution from oblate types. Similarly, for the less luminous sample, values of $\mu_{\ell,0} = 0.45$, $\mu_{p,0} = 0.70$, $\mu_{t,0} = 0.90$, and $\mu_{t,0} = 0.70$–0.75 are derived.

McMillan et al. (2007) pointed out that the axis ratios of equal-mass merger remnants can be different for differing merging conditions. In this case, our result (no significant difference between the two samples in terms of the axis ratios preferred) could be interpreted as a lack of significant difference in the merger history between the samples. However, if it takes numerous merging events to build elliptical galaxies, the memory of the past merger history could easily be buried. The last major/minor merger event, on the other hand, could still be important.

6. DEPENDENCE ON ENVIRONMENT

Within the context of the $\Lambda$CDM scenario, galaxies build up hierarchically via galaxy mergers and interactions. In this regard, the density-morphology relation (Dressler 1980) may reveal the significance of the environment for galaxy formation and evolution. We investigate whether the intrinsic shapes of early types are also related to the environment. We used Joo Heon Yoon’s density parameter ($\rho$) for the local density of early-type galaxies (J. H. Yoon 2007, private communication). Yoon’s density parameter ($\rho$) is a measurement of crowdedness, counting all the
neighboring galaxies with a Gaussian weighting scheme in proportion to the distance between the galaxies. Yoon’s measurements are improved over those of Schawinski et al. (2007), primarily by including more candidate member galaxies and assuming that early-type galaxies obey optical color-magnitude relations. Surprisingly, we did not find any notable impact of the density parameter on the apparent ARD. Even between the two extreme subsamples (representing fields and dense clusters), the apparent ARDs are found to share the same parent distribution via a K-S test. It should be noted that Ryden et al. (1993) reported a similar result, finding no significant difference in the ARD in their sample of brightest cluster galaxies (BCGs).

It is interesting to note that semianalytic models also show consistent results. Khochfar & Silk (2006) assert that the stellar properties of merging remnants of massive galaxies above the characteristic mass (∼ 3 × 10¹⁰ M☉; Kauffmann et al. 2003) are not much different between the field and cluster environments. If we consider the brightness of our sample galaxies, M_r = −19 through −23, and assumed a stellar mass-to-light ratio of 5, most of our galaxies would exceed the characteristic mass.

7. LIMITATIONS

In this section we investigate the limitations of our approach by comparing our results with different classification schemes. A robust result that does not strongly depend on the choice of schemes would ensure the usefulness of the method. Table 1 and Figure 9 show the three cases defined as M1, M2, and M3, where M2 is the Franx et al. (1991) classification scheme that we used in this study.

In Figure 9 we show the apparent ARDs for the three cases, assuming a uniform intrinsic ARD. The peak of each type can change slightly with the classification scheme, but the overall behavior is still retained. In addition, the goodness of fit if we assume uniformly distributed axis ratios is still poor for other cases (χ²red ≈ 50; see § 4.1).

To further constrain the Gaussian parameters, we tested the volume-limited sample, using three different classification schemes. If the dispersion of the preferred axis ratio is too large, no fitting distribution can maintain its full information of the assumed distribution. For example, a Gaussian distribution of oblate galaxies parameterized with μ and σ in the γ-direction would inevitably have galaxies lying outside the oblate territory by the classification scheme (Fig. 1), mostly into the triaxial region. This is particularly so when σ is large and for triaxial elliptical galaxies, due to the type definition. Nevertheless, our exercise showed that the preferred axis ratios and type weights are robustly derived by assuming a Gaussian distribution.

In Table 2, we present the preferred axis ratios (μ) corresponding to the most probable case showing reliable convergence and the Gaussian width (σ) for three different classification schemes. The results on μ and σ appear to be reasonably consistent between M1 and M2, but M3 shows a larger difference. The slight difference in the OPT fractions that is derived is easy to understand. For example, the fractions of the oblate and prolate types in the M3 case are greater than those in M1; this is natural because there are more possible oblate or prolate configurations in M3.

**Table 1**

| Model | Oblate (μ) | Prolate (σ) | Triaxial (κ) |
|-------|-----------|-------------|--------------|
| M1    | 0 ≤ T < 0.15 | 0.85 ≤ T ≤ 1.0 | 0.15 ≤ T < 0.85 |
| M2    | 0 ≤ T < 0.25 | 0.75 ≤ T ≤ 1.0 | 0.25 ≤ T < 0.75 |
| M3    | 0 ≤ T < 0.35 | 0.65 ≤ T ≤ 1.0 | 0.35 ≤ T < 0.65 |

Fig. 8.—Same as Fig. 5, but for two different luminosity groups (see text). The top set of panels shows the ARDs for the luminous sample, and the bottom set of panels are those for the less luminous sample. The majority of the galaxies in the luminous sample are likely triaxial, while a large number of oblate types still exist in the less luminous sample.

Fig. 9.—Same as Fig. 2, but for different classification schemes. The oblate and prolate types are shifted toward the triaxial peak as the classification scheme becomes more generous for the oblate and prolate galaxies.

Fig. 10.—Same as Fig. 10, but for different classification schemes.
We first populate the 4000 sample of 4000 galaxies simulated with the values in Table 2. In Figure 10, we show a mock intrinsic ARD for a classification scheme (see text). This figure shows how the intrinsic ARD changes with the axis; oblate types (prolate types) have Gaussianity on (β). Figure 10 demonstrates how the intrinsic shapes of galaxies that are derived change with classification scheme. Once again, M1 and M2 are similar, but not M3. This demonstrates the currently unsatisfying situation in which the results of our OPT analysis can be sensitive to the choice of the OPT classification scheme. In this sense, it is critical to use a classification scheme that is more physically motivated from kinematic requirements. For example, an ensemble of stellar orbits dominated (by a certain value) by oblate stellar orbits may have a characteristic range in the axis ratios, which could then serve as the unique criterion for “oblate.”

8. CONCLUSIONS AND DISCUSSION

We have investigated the intrinsic shape distribution of early-type galaxies. We show that the deprojection results can be affected by the details of the selection criteria of the observed data. We use a combination of the isophotal major-axis radius, the luminosity, the redshift, and the parameter fracDeV in order to minimize sample biases. We have constructed a volume-limited sample of 4994 early-type galaxies. In addition, since even the high-fracDeV criterion (>0.95) does not completely remove the contamination of non–early-type galaxies, we performed visual inspection on the galaxies and finally selected 3922.

We use the projection probabilities analytically calculated to determine the ratios of oblate, prolate, and triaxial (O, P, and T) types. We found that no combination of randomly distributed OPT types matches the observed ARD.

We have tested a hypothesis of a Gaussian distribution in axis ratios. The results show excellent fits to the observed ARD from our volume-limited sample. In particular, our results show that triaxial is the most common type (W T = 45% ± 12%), and they are round in general (μ T,β = 0.92; μ T,γ = 0.78). On the other hand, the oblate type prefers a more flattened axis ratio (μ O,β = 0.44) and accounts for approximately 29% of all early types. The prolate types show a peak at μ P = 0.72, with a comparable fraction to that of oblate types (26%).

Recent numerical N-body simulations suggest that dark matter halos favor triaxial or prolate shapes over oblate shapes (Dubinski & Carlberg 1991; Barnes 1992; Jing & Suto 2002; Bailin & Steinmetz 2005; Novak et al. 2006). This is consistent with our result at least in the sense that the triaxial type is favored, while a small discrepancy is found in the values of the preferred intrinsic axis ratios. Dubinski & Carlberg (1991) proposed that dark matter halos are triaxial with values of (β) = 0.71 and (γ) = 0.50, respectively, which is somewhat more flattened than what we derived. In order to reproduce the observed ARD using these preferences for triaxial type, specifically designed distributions for the oblate and prolate types would be needed. This is obviously contrived. Interestingly, our results are more comparable with the simulation results of Bailin & Steinmetz (2005), which suggested that γ = 0.6 ± 0.1 and β = 0.75 ± 0.15 for dark matter halos. It should, however, be noted that the mass distribution of halos with cooled baryons can be different from those of pure dark matter halos (Gnedin et al. 2004). Novak et al. (2006) also pointed out the disparity in the halo shape between the stellar and dark matter components. If this is true, the apparent agreement between the axis ratios derived in our study and those from the dark matter simulations may not be significant. Further investigations are called for.

In the context of merging, merger remnants are mainly affected not only by initial orientation, but also by the mass ratio of the merging galaxies (Naab & Burkert 2003; Khochar & Burkert 2006). Bright early-type galaxies are often supposed to be formed via numerous merging events in the ΛCDM cosmology. Hence,
we should investigate the entire possible parameter space in order to make a realistic comparison with observations. In addition, because elliptical-elliptical mergers, as well as spiral-spiral mergers, can lead to the formation of an elliptical galaxy, the parameter space is large. Furthermore, there appear to be two distinct classes of early-type galaxies, separated by their luminosity (Bender 1988; Kormendy & Bender 1996). These studies indicate that luminous galaxies are typically supported by anisotropic velocity and have boxy isophotes, while faint early types show disky isophotes. On this basis, we search for a clue as to their formation history by using the OPT parameters that we derived. Our results indicate that the galaxies in the “luminous” sample (\( M_r < -21.2 \)) are mostly triaxial (\( W_t = 67\% \pm 13\% \)), whereas the “less luminous” sample has a large number of oblate types (38\% \pm 8\%). Interestingly, we find no clear difference in the preferred axis ratios of the OPT types between the two samples.

Khochfar & Burkert (2003, 2005) suggest that the origin of the two classes could come from the different types of progenitor being merged (cf. Valluri & Merritt 1998). Their semi-analytic models suggest that bright early types tend to form from elliptical-elliptical mergers. Naab et al. (2006) also pointed out that spiral-spiral mergers cannot reproduce the observed fraction of anisotropic early types and that boxy, anisotropic systems can form by binary mergers of early-type galaxies. If early-type mergers are the main channels through which to form bright anisotropic galaxies, and if our triaxial galaxies correspond to anisotropic early types, whereas oblate types are rotationally supported systems, our results show reasonable agreement with those of Naab et al. (2006) in terms of the ratio of anisotropic galaxies to the total number of early-type galaxies. The fraction of the anisotropic galaxies in the luminous and less luminous samples is around 0.8 and 0.4, respectively (Naab et al. 2006), which is arguably similar to our results (\( W_t = 0.67 \pm 0.13 \) and \( W_t = 0.43 \pm 0.11 \)).

Since different merging events are proposed to result in different configurations for early-type galaxies, it is also of interest to investigate whether there is a connection between the environment and the galaxy shape. We do not find a clear dependence on the local galaxy density. If we consider that the galaxy number density parameter generally represents the dark matter halo potential for the galaxy cluster, this may imply that such a cluster-scale environment might have little effect on the intrinsic shapes of individual galaxies. This is consistent with the results from the semianalytic study of Khochfar & Silk (2006).

Our analysis has caveats. The quantitative aspects of our simulation results depend on the OPT classification scheme. Besides, when the fraction of a type (oblate, prolate, or triaxial) is small, our method fails to constrain the preferred values of mean axis ratios and Gaussian widths. With improvement on these caveats and detailed study of \( N \)-body simulations, we hope that our work can provide a simple framework from which to investigate the formation history of early-type galaxies.

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