PROPERTIES OF DISKS AND BULGES OF SPIRAL AND LENTICULAR GALAXIES IN THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

A bulge–disk decomposition is made for 737 spiral and lenticular galaxies drawn from a Sloan Digital Sky Survey galaxy sample for which morphological types are estimated. We carry out the bulge–disk decomposition using the growth curve fitting method. It is found that bulge properties, effective radius, effective surface brightness, and also absolute magnitude, change systematically with the morphological sequence; from early to late types, the size becomes somewhat larger, and surface brightness and luminosity fainter. In contrast, disks are nearly universal, their properties remaining similar among disk galaxies irrespective of detailed morphologies from S0 to Sc. While these tendencies were often discussed in previous studies, the present study confirms them based on a large homogeneous magnitude-limited field galaxy sample with morphological types estimated. The systematic change of bulge-to-total luminosity ratio, $B/T$, along the morphological sequence is therefore not caused by disks but mostly by bulges. It is also shown that elliptical galaxies and bulges of spiral galaxies are unlikely to be in a single sequence. We infer the stellar mass density (in units of the critical mass density) to be $\Omega = 0.0021$ for spheroids, i.e., elliptical galaxies plus bulges of spiral galaxies, and $\Omega = 0.00081$ for disks.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters

1. INTRODUCTION

The galaxy consists of two distinct components, disks and bulges, and how they formed is an outstanding problem in the galaxy formation. The classical idea is that elliptical galaxies and bulges, which are altogether called spheroids, formed when infalling gas underwent star formation during the initial collapse of the system, and disks formed from dissipational collapse of the rotating gas that was left over after the initial free-fall collapse (e.g., Eggen et al. 1962; Sandage 1986). Until the early 1970s, it was widely taken that bulges and elliptical galaxies belong to a single population and that elliptical galaxies are spheroids that lack disks for some reasons. This was because the shape and photometric properties of bulges and ellipticals are quite similar.

However, lines of kinematical evidence against the single population hypothesis accumulated since the late 1970s. Illingworth (1977) indicated that bright elliptical galaxies rotate slower than expected from their ellipticities if their velocity dispersion is isotropic. Kormendy & Illingworth (1982) found that bulges of S0 and spiral galaxies rotate more rapidly than bright elliptical galaxies, being consistent with rotationally flattened oblate spheroids with isotropic velocity dispersion. Davies et al. (1983) showed that faint elliptical galaxies also rotate more rapidly than bright elliptical galaxies and that no significant difference is present between the kinematic properties of the bulges and elliptical galaxies with comparable brightness. Bender (1988) discovered that the dichotomy of elliptical galaxies between slow rotators and rapid rotators is more clearly defined by the isophote shape than by luminosity; slow rotators always have boxy isophotes and often brighter than rapid rotators which always have disky isophotes.

Recently, the more popular idea based on the hierarchical clustering scenario says that disk galaxies formed in the center of a dark matter halo as infalling gas collapsed and spheroids are formed via violent mergers (Kauffmann et al. 1993; Baugh et al. 1996). There is also a different view that bulges formed as a result of secular evolution from the disk (Kormendy 1993; Athanassoula 2003; Debattista et al. 2004; Kormendy & Kenicutt 2004; Martínez-Valpuesta et al. 2006; Fisher & Drory 2008; Méndez-Abreu et al. 2008). Lenticular galaxies in between elliptical and spiral galaxies have attracted much attention as to their origins (e.g., Moran et al. 2007). To study the problems of the formation of spheroids and disks, we must collect the statistics as to the properties of the two components and study their regularities—in particular how they vary across early-to-late types—for as many galaxies as possible. The galaxy sample extracted from the Sloan Digital Sky Survey (SDSS; York et al. 2000) based on CCD images provides us with a good database for this purpose at low redshift.

A number of methods have been used for the bulge–disk decomposition. Traditional one-dimensional methods use a surface brightness profile which is extracted from two-dimensional surface brightness distribution by a variety of methods (e.g., Kormendy 1977; Kent 1985, 1986; Simien & De Vaucouleurs 1986; Kodaira et al. 1986). Two-dimensional methods (e.g., de Jong 1996a; Möllenhoff 2004) have been used more recently, and a number of semi-automatic codes have been developed. They include GIM2D (Marleau & Simard 1998; Simard et al. 2002), GALFIT (Peng et al. 2002), BUDDA (de Souza et al. 2004), GASPHOT (Pignatelli et al. 2006), and GASP2D (Méndez-Abreu et al. 2008). Some of them were developed to tackle specific problems for a specific sample of galaxies, while others were intended to be used in more general applications. They differ from each other in many respects such as the number
of components, the fitting function for respective components, minimization algorithm, and the degree of automation.

In the profile decomposition of galaxies, we should keep in mind a caveat that we do not know how well a single-fitting function represents the surface brightness distribution of the component of real galaxies. Thorough investigation of the accuracy and the robustness of these methods is yet to be made (e.g., Pignatelli et al. 2006). Existence of this many codes itself demonstrates the fact that the most suitable method and code depend upon both the problem to be addressed and quality and/or quantity of the data to be analyzed. Generally speaking, the two-dimensional method, while it should give more accurate decomposition, requires accurate galaxy images with high signal-to-noise ratios (S/Ns), and is sensitive to the details of structures. It does not always successfully apply to a large-scale sample where relatively small size images are available.

In this paper, we investigate systematic behaviors of rudimentary properties, i.e., characteristic scales, characteristic brightnesses, and absolute magnitudes, of bulge and disk components along the Hubble sequence by means of a one-dimensional method based not on the surface brightness profile but on the growth curve of galaxies using a large homogeneous sample. We admit that our decomposition may not be quite accurate galaxy-by-galaxy basis, but we believe it gives useful data and provides us with the information for galaxy science so far missing that should be associated with the SDSS data.

2. GALAXY SAMPLE

We take a sample of 1600 galaxies with \( r < 15.9 \) and measured redshift taken from the equatorial stripe 145°15′ < \( \alpha < 235°97′, |\delta| < 1°26′ \) in the northern sky (229.7 square degree), for which morphological classification was carried out by visual inspections. This is an earlier version of the sample in the catalog given by Fukugita et al. (2007), which contains 2253 galaxies with \( r \leq 16 \) in the same region (1866 are given redshift).

Among the 1600 galaxies, 1044 are classified as SO to Sc. From the 1044, we discard 239 galaxies too close to edge-on \((b/\alpha < 0.3)\), 14 galaxies that have bright stars or galaxies overlapped with the galaxy images, 15 galaxies with a lack of growth curve data for some outer parts, and three galaxies with a lack of confident redshift. We also drop 20 galaxies that are not suitable for accurate photometry, either located close to the edge of the survey area or contain saturated pixels. The remaining 753 galaxies were subject to the bulge–disk decomposition, and 737 yielded satisfactory results. The analysis in this paper is thus based on 737 SO–Sc galaxies. The sample we use here does not show any particular bias compared with the \( r < 16 \) morphologically classified sample of Fukugita et al. (2007), except that there are some missing galaxies close to the faint end in our sample.

We use \( r \)-band images drawn from Data Release 3 of SDSS (Abazajian et al. 2005), which do not differ from images in the later data releases for galaxies that concern us. Galactic extinction was corrected according to Schlegel et al. (1998). The number of galaxies for each morphological type used in our analysis is presented in Table 1 together with other statistics that will be discussed in this paper.

We refer the reader to the other publications for descriptions of the SDSS related to our study: Gunn et al. (2006) for the telescope; Gunn et al. (1998) for the photometric camera; Fukugita et al. (1996) for the photometric system; Hogg et al. (2001) and Smith et al. (2002) for external photometric calibrations; Pier et al. (2003) for astrometric calibrations; and Strauss et al. (2002) for spectroscopic target selection for galaxies. We also refer to Abazajian et al. (2003, 2004) and Adelman-McCarthy et al. (2006, 2007, 2008) for other data releases from the SDSS, which discuss the successive improvement of the pipelines used to derive the basic catalogs. We use \( h_70 = H_0/(70 \text{ km s}^{-1} \text{ Mpc}^{-1}) \) unless mentioned.

3. GROWTH CURVE FITTING AND THE BULGE–DISK DECOMPOSITION

The growth curve is the flux integrated within a circular aperture in units of magnitudes as a function of the aperture. It has traditionally been used to estimate total magnitudes (e.g., de Vaucouleurs et al. 1976; RC2). The growth curve should in principle contain the information on profiles of the bulge and disk. The method used here is not new, and the code was developed and tested in Okamura et al. (1999) using simulations and a sample of real galaxies available at that time. Several essential points relevant to the present study are summarized below.

We assume that galaxies are represented by two components, bulges and disks, and their surface brightness \( I \) is described with the de Vaucouleurs law

\[
\log(I/I_{e,B}) = -3.33[(r/r_{e,B})^{1/4} - 1]
\]

for bulges and the exponential profile

\[
\log(I/I_{e,D}) = -0.729[(r/r_{e,D}) - 1]
\]

for disks, where for the two respective components, \( r_{e,B} \) and \( r_{e,D} \) are the effective radii within which half the total flux of each component is contained, and \( I_{e,B} \) and \( I_{e,D} \) are surface brightness at these effective radii.

Departures from the de Vaucouleurs profile (1) are often argued, in particular for late-type spiral bulges (van Houten 1961; Andredakis et al. 1995; Courteau et al. 1996; Trujillo...
et al. 2001; Möllenhoff 2004; Aguerri et al. 2004, 2005; Méndez-Abreu et al. 2008) that the profile of the bulges are somewhat steeper than the de Vaucouleurs profile and an arbitrary power of \( r \) is introduced in the exponent for a general profile (Sérsic 1968). Fittings with a general Sérsic profile, however, is not stable unless the image has a high \( S/N \) over a sufficiently wide dynamic range, causing the degeneracy among parameters, especially between the scale length and power index (see, e.g., Trujillo et al. 2001). Our study is based on the sample of images of a relatively low (at least in terms of conventional bulge–disk decomposition) \( S/N \) with a limited length scale, and it is hard to discern Sérsic-type powers in the bulge component. Hence, we avoid introducing an extra parameter for the bulge profile that controls the power of \( r \). Parameters derived from the fitting are different for different fitting functions used, but they represent virtually the identical physical property if the function is not too far from reality (see the appendix of Kormendy 1977 and Figure 1 of Graham 2001a). The systematic behavior of the parameters along the Hubble sequence, which we focus on in this study, depends only weakly on the specific choice of a particular fitting function.

We note that a two-dimensional fitting for the bulge with the Sérsic profile shows that 2/3 of galaxies have \( n = 4 \), i.e., the de Vaucouleurs profile as the best-fit solution (Tasca & White 2005), so that the error for the global mean arising from the assumption enforcing \( n = 4 \) is not too large.

Another issue of concern is the effect of bars. Our growth curve method is a one-dimensional method based on a series of circular apertures. Accordingly, information on the elliptical surface brightness distribution of a bar is "degenerated" onto an equivalent circular surface brightness distribution of a "hypothetical" bulge. This means that in the case of a barred galaxy, we regard the bar plus bulge as a single entity, which we call bulge here. This point is discussed further in Section 4.

For the growth curve method to work properly it is essential to include the effect of finite seeing, which we take to be double Gaussian (that is, the SDSS default) and parameterize for our purpose its full width at half-maximum \( w_\text{s} \) as its ratio to the effective radius of the disk

\[
\zeta = \log(r_{\text{e},D}/w_\text{s}).
\]

The seeing parameters are cataloged for each galaxy in the SDSS database.

For our application, we prepare templates for 11 grid points for each of the three parameters, \( B/T = 0–1, \eta = \log(r_{\text{e},B}/r_{\text{e},D}), -1.2 < \eta < 0.8, \) and \( 0 < \zeta < 2.0 \). The ranges of the parameters are chosen so that the results are well covered in these ranges. We then compute

\[
\chi^2 = \sum_{i=3}^{N} w_i \left[ m(\log r_i) - m_{\text{tot}} - \Delta m \left( \log r_{\text{e}} \right) \right]^2 + \frac{1}{4} \left[ \log r_e - \log r_e^T \right]^2.
\]

where the template was swept over all 1331 grids with the parameters \( B/T, \eta, \zeta \), together with two free parameters, \( m_{\text{tot}} \) and \( r_e \), searched to get the best fit to the growth curve data for each template. Here, \( m_{\text{tot}} \) is the total magnitude, and \( r_e \) is the half-light radius of the galaxy, while \( r_e^T \) is the half-light radius of the assumed template. The weight factor is taken to be \( w_i = \log r_i \). The last two terms are added to avoid a fake fit with a rather unrealistic template to ensure that the best-fit parameter for the effective radius is close to the one adopted as a template. We use the data at 13 apertures from 1.03 to 263 arcsec with approximately a geometric sequence by a factor of 1.5, measured from the fitting, as they are substantially smaller than median seeing, \( 1''3 \), and strongly susceptible to seeing, \( w_\text{s} \) is known for each galaxy, so that \( r_{\text{e},D} \) and \( r_{\text{e},B} \) are obtained from \( \zeta \) and \( \eta \) of the template that gives the best fit to growth curves. We apply the \( K \)-correction to the image, though all galaxies have small redshift \( z < 0.1 \), taken from Fukugita et al. (1995) assuming bulges to have elliptical color and disks Scd color. Their \( K \)-corrections are consistent with the mean of those calculated using individual spectra (Blanton et al. 2003), and the redshifts are so low that errors are negligible.

Extensive simulations show that this growth curve method can be used to determine bulge and disk parameters and bulge-to-disk luminosity ratios provided that the point-spread function is accurately known and the \( S/N \) is modest, say \( S/N \geq 30 \) (Okamura et al. 1999). It is shown that the accuracy of the derived parameters depends upon inclination, bulge-to-disk ratio, surface brightness, available image area, and also other factors in addition to \( S/N \). It is, therefore, in general, difficult to quote a few numbers to represent the robustness of the method. Another example of the similar presentation can be seen in Pignatelli et al. (2006), where the robustness is estimated as a function of the threshold area, instead of \( S/N \), of galaxy images. The present sample is limited to galaxies with \( r < 15.9 \), which roughly corresponds to \( S/N > 200 \) (see Figure 2 of Okamura et al. 1999), and does not include highly inclined \( b/a < 0.3 \) galaxies. Accordingly, we can expect a reasonable robustness for the present sample. Fit to each of the sample galaxies is visually examined.
For a verification of the fit, we show the difference between the Petrosian magnitude measured by the SDSS photometric pipeline and the total magnitude obtained from the present fit as a function of $B/T$ in Figure 1(a), and the effective radius $r_e$ with respect to the Petrosian half-flux radius $r_{ps0}$ as a function of the $B/T$ in Figure 1(b), where the plotted radii from the fit are corrected for finite seeing to compare with the measured Petrosian radii. Note that we expect $m_p - m_{tot} = 0.221$ and 0.007 for the ideal de Vaucouleurs and exponential profiles that are located face on, which are indicated by horizontal lines in the figure. For inclined galaxies, these offsets are slightly (~5%) smaller. The data for magnitude offsets in Figure 1(a) are located mostly in between 0 and 0.2 mag, with a trend for an increase to 0.2 mag toward a larger $B/T$ in agreement with our expectation.

For the effective radii, we expect $r_{ps0}/r_e = 0.713$ for de Vaucouleurs galaxies and $r_{ps0}/r_e = 0.993$ for exponential galaxies for the face-on case. Our data in Figure 1(b) that are located mostly between 1 and 1.3 with relatively larger values for bulge dominated galaxies, as expected. There are a small number of cases where deviations are significant. We have examined images of those cases and found that they happen occasionally for large-size late-type galaxies, for which PHOTO gives too small radii which do not seem to be correct. This is probably due to errors in the measurement by PHOTO which are caused by too marked contrasts with bright bulges. Those data points in Figure 1(a), whose Petrosian magnitudes are somewhat too dim, also correspond to the deviants in Figure 1(b), and the same reason is suspected. Together with the figure for total magnitudes our result means that the fit gives a reasonable value for both total flux and effective radius, and our assumption for galaxies that are represented by exponential plus de Vaucouleurs profiles works reasonably well.

We adopt the morphological-type index $T = 0$ for E, $T = 1$ for S0, $T = 2$ for Sa, $T = 3$ for Sb, $T = 4$ for Sc, and $T = 5$ for Sd, since the $T$ index as detailed as that in the RC2 is not warranted for both our catalog and purpose here. Galaxies of classes with a half integer $T$ are grouped into the neighboring later class except for $T = 0.5$ (E/S0), which shows an unclear sign of disks and is discarded in our decomposition analysis. The morphological index given in Fukugita et al. (2007) is based on visual inspections of $g$-band images by several independent classifiers in reference to prototypes presented in the 

![Hubble Atlas of Galaxies (Sandage 1961)]. The mean index by the several classifiers is given in the catalog, which we take in the present work.

Our prime interest is to study the change of properties of bulge and disk against morphology, but our sample is large enough to attempt to study the change of properties of the bulge and disk against luminosity. We make three subsamples ($-23 < M_r < -22$, $-22 < M_r < -21$, and $-21 < M_r < -20$), dividing the sample into three luminosity groups; they stand for nearly luminosity-limited samples with varying distance limits.

4. RESULTS

4.1. Bulge-to-Total Luminosity Ratio

Figure 2 presents the bulge-to-total luminosity ratios ($B/T$) as a function of the morphological-type index $T$. The mean and dispersion are shown by error bars for each morphological type, where $T$ runs from 1 for S0 (excluding E/S0) to 4 for Sc (including Sbc). In order to assess the effect of bars discussed in Section 3, we examine all the galaxy images and classified them into barred and non-barred. Except for $T = 1$ (S0), where only three barred galaxies are present, no systematic difference is found between barred and non-barred galaxies. This is probably due to the fact that the elliptical structure of bars disappears in the growth curve obtained in circular apertures as mentioned in Section 3. Laurikainen et al. (2007) found some difference in $B/T$ versus Hubble-type between early-type barred and non-barred spiral galaxies. However, their data are based on near-infrared images, and a direct comparison is inappropriate.

One can see a good correlation showing that an earlier type shows a larger $B/T$, 0.64 for S0, decreasing for late types to 0.19 for Sc. This agrees broadly with the results given by a number of authors (e.g., Kent 1985, 1986; Simien & de Vaucouleurs 1986; Kodaira et al. 1986, and others), although an accurate comparison needs a translation as to different color bands used by respective authors. The numbers for S0 and Sc, 0.64 and 0.19, are, for instance, compared with 0.75 $^{+0.1}_{-0.3}$ of Kent (1985), who used Thuan–Gunn $r$ band that is close to ours. The dispersion for $B/T$ in each class, approximately ±0.2, denoted by error bars, however, is larger than the interclass differences. This also agrees with what is known from analyses made in the past: the scatter in each class is larger than the difference of the average among different classes. This means that, while $B/T$ is well correlated with morphological types, we cannot replace the morphological types for individual galaxies with $B/T$, although $B/T$ provides a convenient measure and is often used to classify morphological types (e.g., Tasca & White 2005), especially in theoretical modeling (e.g., Baugh et al. 1996). It is tempting to ask if this systematic variation of $B/T$ is ascribed to the property of the bulge or the disk, or both. This question is answered in the subsections that follow.

4.2. Properties of Bulges

The two key parameters that characterize the bulge are the effective radius $r_{e,B}$ and $\mu_{e,B}$, which is surface brightness at $r_e$. It was shown that these parameters for elliptical galaxies obey some $\mu_{e,B}$–$r_e$ relation (Kormendy 1977). We show in
The selection of early-type galaxies by Bernardi et al. (2003) is rather rudimentary to deal with a large sample. It contains not only E and S0 galaxies but also many Sa galaxies, when compared with the visually classified sample. The sample, however, is certainly rich in E and S0 galaxies, and we expect that statistical quantities derived from the sample give a reasonable approximation. We also note that the sample suffers from a significant incompleteness for early-type galaxies fainter than $M_B \simeq -21$.

Bulges of later-type spiral galaxies ($\mu_e, r_e$) are distributed along lines that are significantly steeper, nearly along the line of constant luminosity, $I_e r_e^2 = \text{constant}$, or $\mu_e = 5 \log r_e + \text{constant}$, with a significantly scatter larger than S0 bulges. It is known that there is a dichotomy in elliptical galaxies in terms of kinematical structure: slow rotators versus rapid rotators (e.g., Kormendy & Illingworth 1982; Davies et al. 1983; Davies & Illingworth 1983). Slow rotators have boxy isophotes, while rapid rotators have disky isophote (Bender 1988). This dichotomy is also closely related to luminosity; bright ellipticals are often slow rotators, while faint ellipticals tend to be rapid rotators with the boundary at $M_B \sim -20.5$ mag. The $\mu_e - r_e$ relation of rapid rotators is not well known since even the SDSS sample, by far the largest sample of early-type galaxies, contains only a small fraction of ellipticals fainter than $M_B \sim -20.5$ ($M_R \sim -22$). Whether or not the bulges of late-type spiral galaxies and rapidly rotating faint ellipticals follow a similar $\mu_e - r_e$ relation is at present an open question.

If we consider the mean ($\mu_e, r_e$), we see a trend (see Figure 4) for different morphological classes: bulges for late-type spirals have surface brightness dimmer than that for early types, whereas the effective scale length of bulges differs little. The bulge surface brightness of Sc spirals is dimmer by 2 mag arcsec$^{-2}$ than that for S0 or Sa. Surface brightness of Sa bulges, however, is nearly the same as that for S0 bulges. The bulge luminosity for late-type spirals is also lower by 2 mag than that for S0’s.

It is noted in passing that no systematic difference is found between barred and non-barred galaxies. When the plot is made separately, they are distributed over the same area in the $(\mu_e, r_e)$ plane.

### 4.3. Properties of Disks

A similar figure for $(\mu_e, r_e)$ is shown for disks in Figure 5. The data are apparently distributed more clustered in a narrower
region than for bulges: a rough trend \( I_e r_e^2 \sim \text{constant} \) is still visible, but the data are distributed in narrower ranges. The mean surface brightness is \( \mu_e, D = 22.06 \text{ mag arcsec}^{-2} \) with the dispersion 0.96 mag arcsec\(^{-2}\). No systematic difference is found here either between barred and non-barred galaxies in their distribution in the \((\mu_e, r_e)\) plane.

Figure 6 shows the mean and dispersion of \((\mu_e, r_e)\) for each morphological type, indicating that the properties of disks change little against morphologies; at least the change is not systematic along the morphological sequence. The disk luminosity also differs little across S0–Sc. For example, properties of disks for S0 and Sc galaxies differ very little: the difference among different morphology classes is much smaller than the scatter from galaxy to galaxy in one class. Surface brightness of S0 may be slightly fainter than that of later spiral galaxies but much less so than the bulge. In fact, bulge luminosity is the main variable that controls morphology. A large and conspicuous bulge means the galaxy being an early type. In contrast, the properties of disks are nearly universal and depend little on morphology.

These systematic behaviors of bulge and/or disk parameters were found in previous studies based on various samples of galaxies (e.g., Kodaira et al. 1986; de Jong 1996a; Graham 2001a, 2001b; Möllenhoff & Heidi 2001; Trujillo et al. 2002; Aguerri et al. 2004; Laurikainen et al. 2007; Méndez-Abreu et al. 2008; Graham & Worley 2008). The size of these samples ranges several tens to about 200, and some are limited to cluster members. Our study confirms the behaviors that have been referred to in the literature based on a much larger homogeneous magnitude-limited sample in the field. An accurate quantitative comparison needs translation as to different color bands as well as specific bias arising from different methods adopted by different authors.

It is interesting to note that the morphological-type dependence, as we have seen with bulges, almost disappears for disks. Disks in both early- and late-type spiral galaxies, including S0’s, are similar with nearly constant surface brightness and scale length independent of the disk galaxy morphology.

### 4.4. Summary: Bulge and Disk Properties versus Morphological Type

The most conspicuous fact is that the bulge-to-disk or \( B/T \) depends on morphology of spiral galaxies. Later-type spiral galaxies are more disk dominated, which is in agreement with the widely accepted concept. We have found that the properties of disks, including luminosity, do vary little with morphology. This implies that the property that varies with morphology is the bulge; in fact bulge luminosity is the main variable that controls morphology. A large and conspicuous bulge means the galaxy being an early type. In contrast, the properties of disks are nearly universal and depend little on morphology.

The systematic behaviors found here and in some previous studies may imply that the formation of disks takes place independent of bulges. The infall of intergalactic gas, for example, takes place irrespective of bulge properties. Some self-regulating mechanisms are suspected to be at work in disk that limit the accumulation of too many stars per area of the disk.

We do not see any trend that later-type disks have higher surface brightness. In particular, surface brightness of S0 disks differs little from that of Sa disks, in contrast to the claim that Sa disks have surface brightness much brighter than S0 disks (Sandage 1986), as expected in the monolithic collapse scenario. Surface brightness of Sa and that of Sc are also nearly identical on average. We see no signatures that Sb–Sc disks are less luminous than that of S0–Sa, which could result if disk stars are transported to bulges by secular formation of bulges from disks in late-type spiral systems (Kormendy 1993; Kormendy & Kennicutt 2004).

It is also interesting to note that surface brightness of S0 galactic disks differs little from that of other spiral galaxies. The majority of S0’s disks are unlikely to be a result of stripping
of spiral galaxies (Larson et al. 1980) or faded spiral galaxies (Bedregal et al. 2006): S0’s, at least for their majority, are not a result from spiral galaxies that lost substantial disk ingredients.

4.5. Correlation between Scale Lengths

The evidence has been discussed that the disk scale length correlates with the bulge scale length, and it is taken as evidence that suggests disk origin of bulges by secular evolution of disks (Courteau et al. 1996; Méndez-Abreu et al. 2008): galaxies with a large-size bulge may necessarily have large-size disks. In our sample, we have not seen any particular correlation between the two scale lengths. The correlation, if any, is weak.

The disk scale lengths are distributed dominantly between 2 and 10 kpc, and the bulge scale lengths between 0.2 and 6 kpc. The ratio \( r_{e,B}/r_{e,D} \) is distributed in the range of 1–10 with very broad peaks whose center is around 0.3 (see Figure 7 for histograms for \( r_{e,B}/r_{e,D} \)). This might be taken as the evidence of correlations between the two scale lengths, but in fact does not mean the presence of a particular correlation between the two scales: it is a result of a fact that the two scales are distributed independently in narrow ranges. We do not observe close correlations between quantities characterizing bulges and disks, implying that disks formed independently of the details of bulges.

4.6. Properties of Disks and Bulges as Luminosity Varies

We carried out the same analysis with the three luminosity group samples. The trends we observed in this section for the total sample are still visible with the luminosity-grouped samples, and the overall trends differ little from that we have seen for the total sample. The three panels in Figure 8 give the change against total luminosity of galaxies.

First we see (Figure 8(a)) that the change of the bulge-to-total flux ratio against the total luminosity. The change is only little, \( \sim 20\% \), even for S0 galaxies, where the bulge largely controls the total luminosity. The change is hardly discernible for later-type spiral galaxies. This result means that luminosities of both bulges and disks change as total luminosity changes in a similar way (and in a lesser degree for disks), so that the ratios stay nearly at constants.

Bulges of fainter galaxies are also fainter by the same amount, but the reason is not uniform (see Figure 8(b)): in early-type disk galaxies, S0 and Sa, this change arises more from the decrease of the size, fainter galaxies having smaller bulges, but in later types dimmer bulge magnitude is ascribed primarily to dimmer surface brightness rather than smaller bulge sizes, which remain a constant independent of luminosity.

Luminosities of disks change as the total luminosity changes in nearly the same way (less in earlier systems). The change of disk luminosity is mostly caused by the decrease of the size (effective radius), while surface brightness at the effective radius stays nearly unchanged: the change of \( \mu_e \) is less than \(-0.3\) mag arcsec\(^{-2}\) for a 2 mag change of disk luminosity (the change of surface brightness takes place in the opposite direction). See Figure 8(c).

5. LUMINOSITY DENSITY

Nakamura et al. (2003) estimated that the luminosity densities of early- and spiral-type galaxies to be

\[
L_r(E + S0) = 0.43 \times 10^4 h_{70} L_\odot \text{ Mpc}^{-3},
\]

\[
L_r(S) = 0.96 \times 10^5 h_{70} L_\odot \text{ Mpc}^{-3}.
\]

These values and all the numbers up to and including Equation (10) should be multiplied by 1.29 for the global values.
to correct for the underdensity of galaxies in the northern equatorial stripes where the luminosity function (and also present work) was derived from. Assuming that the shape of the luminosity functions changes little within rough classes of morphology according to Nakamura et al. (2003) and using their luminosity densities up to the normalizations, we infer that

\[ L_\star(S0, \text{bulge}) = 0.18 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3}, \]

\[ L_\star(S0, \text{disk}) = 0.10 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3}, \]

where \( E : S0 + E/S0 = 0.36 : 0.64 \) from Fukugita et al. (2007), and \( B/T \) of S0 is 0.64 from Figure 2, and the luminosity fractions given in Section 3 are assumed to be independent of luminosity and are used to compute the bulge and disk contributions. The luminosity density of elliptical galaxies is

\[ L_\star(E) = 0.15 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3}. \]

For spiral galaxies, Nakamura et al. give \( L_\star(S) = 0.70 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3} \) for S0/a–Sb galaxies and 0.26 \( \times 10^8 h_{70} L_\odot \text{Mpc}^{-3} \) for Sbc–Sd galaxies. Assuming the \( B/T \) for Sd–Sdm (which contribute by only 13% to the luminosity density of Sbc–Sdm galaxies) being equal to that for Sc galaxies, we use 0.19 for \( B/T \) of Sbc to Sd galaxies. We also assume \( B/T \) of S0/a–Sb galaxies to be 0.43 as an approximate mean in the morphology range. These values enable us to infer the luminosity densities for spiral galaxies in the same way, and we obtain

\[ L_\star(S + S0, \text{bulge}) = 0.53 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3}, \]

\[ L_\star(S + S0, \text{disk}) = 0.71 \times 10^8 h_{70} L_\odot \text{Mpc}^{-3}. \]

Therefore, contributions to the luminosity density from disk, bulge, and elliptical galaxies are 0.51:0.38:0.11, respectively.

This result may be compared with 0.54:0.14:0.32 from Tasca & White (2005). The disagreement in the spheroidal contributions is ascribed to the fact that a significant amount of S0 galaxies are counted as pure bulge systems, i.e., elliptical galaxies, in Tasca & White (2005). Intrinsically bright galaxies are very often regarded as pure bulge systems with nearly edge-on disks greatly under-represented in the application of the Gim2D code. When spheroids include elliptical galaxies and bulges, the relative contributions to disk and spheroids 0.53:0.47 in our analysis agree with the fraction given by Tasca & White.

If we use a result of stellar population synthesis (Bruzual & Charlot 1993) assuming two populations in the universe—spheroids and disks—constrained with the mean colors of SDSS galaxies (Nagamine et al. 2006), we have the average stellar mass-to-light ratios, \( \langle M_\star/L_\star \rangle = 3.2 \) for spheroids and 1.2 for disks, or correspondingly \( \langle M_\star/L_h \rangle = 5.6 \) and 1.2, respectively, if the more familiar \( B \) band is adopted. Using these mass-to-light ratios and including the fraction of 1.29 correction and \( h_{70} = 1 \), we estimate the stellar mass density

\[ \Omega_{\text{spheroids, star}} = 0.00207, \]

\[ \Omega_{\text{disk, star}} = 0.00081, \]

i.e., the total stellar mass density \( \Omega_{\star} = 0.0029 \) and the ratio of two mass densities \( \Omega_{\text{spheroid, star}}/\Omega_{\text{disk, star}} = 2.6 \). The latter is somewhat smaller than the ratio in Fukugita et al. (1998), who gave 3, but substantially larger than 0.77 by Benson et al. (2002) and 0.75 by Driver et al. (2007).

6. CONCLUSIONS

We have carried out bulge–disk decomposition for a modestly large sample of galaxies derived from a morphologically classified sample of the SDSS with the use of growth curve fitting. We demonstrated that growth curve fitting method works as expected and studied properties of bulges and disks thus decomposed as functions of morphology and luminosity. We endorsed the well-known trend that the importance of bulge decreases systematically from early to late types, but we have shown that this is dominantly due to the variation of bulges as the morphological type changes. In contrast, we have shown that the properties of disks are nearly universal, and depend only weakly on morphology classes. We do not see any systematic trend of disks that changes with morphology of disk galaxies. In spite of a good correlation between the \( B/T \) and the morphological type, the galaxy-to-galaxy scatter of the former is so large that one cannot replace the conventional morphology type with the luminosity ratio.

While we have a number of different scenarios for disk and bulge formation, definitive predictions that can be compared with our analysis are not readily available. However, a number of predictions or likely results seem to be disfavored. For example, the monolithic scenario that the bulge formed from infall of gas and the disk formed from dissipational collapse of gas left over the initial collapse favors brighter disks for later type morphologies. This is not supported by our data. The model that S0 forms as a result of stripping of spiral disks or spiral galaxies of faded disks is not favored either, since disk properties of spirals are all similar including S0’s. We do not observe any conspicuous change in disk properties between early- and late-type spiral galaxies, which would be expected if late-type spiral bulges are a product of secular evolution from disks, while earlier types are from major mergers. Furthermore, we do not see correlation between bulge and disk properties.

The universal disks that we have seen may be more consistent with the naive idea that disks are later additions by accretion of intergalactic material falling onto bulges where accretion took place independent of bulge properties, but with some self-regulating mechanism that limits the column density of stars in the disk.

We also noted that the properties (\( \mu_e, r_e \)) of bulges of spiral galaxies and bright elliptical galaxies are different, obeying different relations, which implies that bulges and bright elliptical galaxies are unlikely to be on a single sequence.

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APPENDIX

STELLAR POPULATION SYNTHESIS

The bulge–disk decomposition enables us to infer color of galaxies with two population of stars, disk stars and bulge stars. We approximate them as a delayed exponential model, i.e., star formation being given by $\rho(t) = A(t/\tau) \exp(-t/\tau)$ (Searle et al. 1973; Nagamine et al. 2006). We may adopt the parameters given by Nagamine et al. (2006) which gives global the University of Washington.

Figure 9. $g-r$ color (left) and $u-g$ color (right) of galaxies in various morphological types. The curves are prediction based on the bulge–disk decomposition given in this paper with the aid of the stellar population synthesis with a delayed exponential star formation model. The data with error bars (variance) are statistics from morphologically classified sample of SDSS galaxies.

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$M_*/L_r = 1.18 + 2.01(B/T)$, (A1)

where $B/T$ is the bulge fraction of luminosity given in Table 1, and Chabrier’s initial mass function (Chabrier 2003) is used to calculate the stellar mass.
