The nature of the SDSS galaxies in various classes based on morphology, colour and spectral features – I. Optical properties

Joon Hyeop Lee1,2*, Myung Gyoon Lee1*, Changbom Park3*, Yun-Young Choi4*
1Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea
2Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
3Korea Institute for Advanced Study, Dongdaemun-gu, Seoul 109-722, Korea
4Astrophysical Research Centre for the Structure and Evolution of the Cosmos, Sejong University, Seoul 143-747, Korea

ABSTRACT
We present a comprehensive study of the nature of the SDSS galaxies divided into various classes based on their morphology, colour, and spectral features. The SDSS galaxies are classified into early-type and late-type; red and blue; passive, H II, Seyfert, and LINER, returning a total of 16 fine classes of galaxies. We examine the luminosity dependence of seven physical parameters of galaxies in each class. We find that more than half of red early-type galaxies (REGs) have star formation or AGN activity, and that these active REGs have smaller axis ratio and bluer outside compared to the passive REGs. Blue early-type galaxies (BEGs) show structural features similar to those of REGs, but their centres are bluer than REGs. H II REGs are found to have bluer centres than passive REGs, but H II REGs have bluer outside than passive REGs. Bulge-dominated late-type galaxies have red colours. Passive red late-types are similar to REGs in several aspects. Most blue late-type galaxies (BLGs) have forming stars, but a small fraction of BLGs do not show evidence for current star formation activity. Differences of other physical parameters among different classes are inspected, and their implication on galaxy evolution is discussed.

Key words: galaxies: general – galaxies: evolution – galaxies: statistics – galaxies: elliptical – galaxies: spiral – galaxies: active

1 INTRODUCTION
One of the fundamental issues of the observational cosmology is the evolutionary connection between various classes of galaxies. Today, galaxies are classified with various criteria. The most classical classification of galaxies is the Hubble sequence: elliptical galaxies, lenticular galaxies, spiral galaxies, barred spiral galaxies, and irregular galaxies (Hubble 1936; Sandage 1961; De Vaucouleurs 1974). The main criterion of this classification is the morphology of galaxies; that is, the existence, size ratio, and appearance of spiral arms, disc, bulge, and bar. The Hubble sequence was established mainly based on the galaxies without nuclear activity, and such galaxies are often called normal galaxies. On the other hand, more and more galaxies showing active nuclei with broad line emission are being found; they are often called abnormal galaxies. According to the features of the line emission, active galactic nuclei (AGN) host galaxies are classified into several sub-classes: Seyfert 1 galaxies, Seyfert 2 galaxies, broad-line radio galaxies, narrow-line radio galaxies, low ionisation nuclear emission regions (LINERs), and so on. Luminosity is another criterion to classify galaxies. Sandage & Binggeli (1984) defined the galaxies with \( M_B > -18 \) as dwarf galaxies. In addition to those general classes of galaxies, there are some unusual galaxy classes with interesting properties: E+A galaxies with the spectral features of both very old stellar populations and very young stellar populations (Dressler & Gunn 1992; Yang et al. 2006, 2008); ultra-luminous infrared galaxies (ULIRGs) that are very bright in the mid- and far-infrared bands (Sanders & Mirabel 1996; Hwang et al. 2007); blue compact galaxies that show very compact morphology and high surface brightness with blue colour (Thuan et al. 1997); extremely red objects (EROs) whose optical – infrared colour is extremely red (Elston et al. 1983), and so on. Recently, to deal with a large amount of survey data, many astronomers have classified galaxies simply into red se-
quence galaxies and blue sequence galaxies according to their colour-magnitude relation (e.g. Martin et al. 2007).

For a long time, the individual properties of galaxies in those various classes have been investigated, and many efforts have been made to answer fundamental questions about galaxy evolution and connections between galaxy classes. Some examples of such fundamental questions are as follows: Why is there a conspicuous bimodality in the colour distribution of galaxies? Why does the colour bimodality not exactly agree with the morphological segregation? How do the environments affect the properties of galaxies? How did active galactic nuclei (AGNs) form? Is there any transition among the different classes of galaxies? Recent studies using large survey data discovered several interesting aspects of galaxy evolution, providing some answers to those fundamental questions.

For example, Ball et al. (2006) studied the bivariate luminosity functions with galaxy type classification, and found that there is a clear morphological bimodality supporting the idea that merger and accretion are associated with bulges and discs, respectively. Bernardi et al. (2003) showed that both luminosity and colour of early-type galaxies are correlated with stellar velocity dispersion, and that velocity dispersion may be also closely correlated with the age and metal abundance of early-type galaxies. Choi et al. (2007) found that late-type galaxies show wider dispersion in several physical quantities than early-type galaxies, and that those physical quantities manifest different behaviours across $M_z \pm 1$ mag. Park et al. (2007) investigated the environmental effects on various physical properties of galaxies, finding that a key constraint on galaxy formation models is the morphology-density-luminosity relation. Mateus et al. (2006) analysed the colour, 4000 Å break, and age in various spectral classes of galaxies, suggesting that the median light-weighted stellar age of galaxies is directly responsible for the colour bimodality in the galaxy population.

Those previous studies, however, are not yet enough to explain the origins of the various galaxy classes and the evolutionary connections between the classes. One of the major limitations is that the galaxy classifications in most previous studies were often limited to only one or two properties. For instance, automatically-classified morphology (e.g. Park & Choi 2003; Ball et al. 2006), galaxy colour (e.g. Martin et al. 2007), or spectral line features (e.g. Mateus et al. 2006) are used frequently in recent studies based on large survey data, but a multilateral classification study using all these criteria at the same time has not yet been seen. Such simplifications may be very useful to understand the various and complicated phenomena in galaxy evolution. However, a simple classification can not distinguish detailed aspects of galaxy evolution. For example, early-type galaxies are often regarded as red and passive galaxies in most studies, but that is not always true. Some kinds of galaxies with early-type morphology were found to have blue colours possibly originating from young stellar populations or active nuclei (Abraham et al. 1999; Im et al. 2001; Ferreras et al. 2003; Lee et al. 2006). It is difficult to understand these kinds of unusual classes in studies with simple classifications.

Closely related to galaxy classification, a couple of studies searching for principal components of galaxy properties have been conducted recently. Ellis et al. (2005) examined the distribution of photometric, spectroscopic and structural parameters for 350 nearby galaxies using the Millennium Galaxy Catalogue (Liske et al. 2003), arguing that most properties show a clear distinction between early-type galaxies and late-type galaxies. Later, Conselice (2006) carried out principal-component analyses of the properties of 22000 galaxies at $z < 0.05$ using the Third Reference Catalogue of Bright Galaxies (RC3; De Vaucouleurs et al. 1991), finding that the three parameters determining a galaxy’s physical state may be mass, star formation and interactions/mergers. These studies presented how useful to consider various parameters in galaxy classification, although some important components like AGNs were not considered in their analyses. Conselice (2006) showed that multiple independent components, rather than any single component, may determine the various properties of galaxies.

Therefore, to understand the nature of galaxies more comprehensively and to give stronger constraints on galaxy evolution models to explain all kinds of galaxies, it is necessary to investigate the nature of galaxies in various and finely-divided classes, and to find out the evolutionary connections between the classes. We have been doing a comprehensive study on a set of fine galaxy classes in the Sloan Digital Sky Survey (SDSS; York et al. 2000), based on their morphology, colour and spectral features. In this paper, the first in the series, we present the optical properties of galaxies in various fine classes. The outline of this paper is as follows. Section 2 shows the data set we used, and §3 describes the methods to classify the SDSS galaxies and to select volume-limited samples. We present the statistics of selected optical parameters and their luminosity dependence in §4. Based on the optical properties, we discuss the nature of galaxies in the fine classes in §5. Finally, the conclusions in this paper are given in §6. Throughout this paper, we adopt the cosmological parameters $h = 0.7$, $\Omega_L = 0.7$, and $\Omega_M = 0.3$.

2 DATA AND PHYSICAL PARAMETERS

We use the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2004) in this study. The DR4 imaging data cover about 6670 deg$^2$ in the ugriz bands, and the DR4 spectroscopic data cover 4783 deg$^2$. The photometric and spectroscopic observations were conducted with the 2.5-m SDSS telescope at the Apache Point Observatory in New Mexico, USA. The median width of the point-spread-function in the $r$ band photometry is 1.4″, and the wavelength coverage in the spectroscopy is 3800 – 9200Å. We use the photometric and structural parameters from the SDSS pipeline (Stoughton et al. 2002) data, and the spectroscopic parameters from the Max-Planck-Institute for Astronomy catalogue (MPA catalogue: Kauffmann et al. 2003a; Tremonti et al. 2004; Gallazzi et al. 2000). In addition, we use the velocity dispersion estimated using an automated spectroscopic pipeline called idlspec2d version 5 (D. Schlegel et al. 2008, in preparation), and colour gradient, inverse concentration, and axis ratio of the SDSS DR4plus (Choi et al. 2007).

1 See http://www.sdss.org/dr4/
3 ANALYSIS

3.1 Galaxy classification

In this study, we classified galaxies with three criteria: morphology, colour, and spectral line features.

Morphology is one of the most fundamental criteria to classify galaxies. We selected early-type galaxies with the galaxy classification method using the colour versus colour-gradient space (Park & Choi 2005) as shown in Fig. 1. In this classification method, colours and colour gradients are the main criteria for classification, and the inverse concentration cut is also applied differentially for different magnitude ranges: R50/R90 < 0.43 for 14.5 < rpet < 16.0, R50/R90 < 0.45 for 16.0 < rpet < 16.5, R50/R90 < 0.47 for 16.5 < rpet < 17.0, and R50/R90 < 0.48 for 17.0 < rpet < 17.5.

The galaxy colour is another classification criterion that is frequently used in large galaxy surveys. We classified the galaxies into red galaxies and blue galaxies, based on the \((g - r)\) colour. Since the \(r\) band is the standard band in the SDSS photometry and the photometric uncertainty in the \(u\) band is relatively large compared to that in the \(g\) band, we selected the \((g - r)\) colour as the index for the galaxy colour segregation. We used the method of Lee et al. (2006) to segregate blue galaxies from red galaxies. First, we divided the redshift range of 0 ≤ z < 0.4 into eight bins, and derived a 0.1K\((g - r)\) colour histogram of the early-type galaxies with the peak at 0.1K\((g - r)\) distribution of early-type galaxies at 8 redshift bins between z = 0 and z = 0.4. The dashed line is the (peak - 3σ) line, which is used for red/blue galaxy separation.

\(^2\) Rpet is the Petrosian radius, and R50 (R90) is the semimajor axis length of an ellipse containing 50 per cent (90 per cent) of the Petrosian flux.
In spectroscopic studies, the line features of galaxies are often used to classify galaxies. Based on the spectral line features, we classified the galaxies into passive galaxies, HII galaxies, Seyfert galaxies and LINER galaxies.

First, we selected AGN host galaxies using the line flux ratio diagram of [O\text{III}]/H\beta versus [N\text{II}]/H\alpha (BPT diagram; Baldwin et al. [1981]) as shown in Fig. 3. We used an empirical criterion to segregate AGN host galaxies from star-forming galaxies: [O\text{III}]/H\beta = 0.61/[N\text{II}]/H\alpha − 0.05 + 1.3. AGN selection was conducted for the sample of galaxies with a signal-to-noise ratio (S/N) of \( \geq 3 \) for H\alpha, H\beta, [O\text{III}] and [N\text{II}] lines (Kaufmann et al. [2003b]), but we classified some galaxies as AGNs even if their S/N ratios of one or two lines are smaller than 3, in some special cases. For example, a galaxy with log([N\text{II}]/H\alpha) > −0.2 and its S/N ratios of [N\text{II}] and H\alpha larger than 3 but with its S/N ratios of [O\text{III}] and H\beta smaller than 3, was classified as an AGN host galaxy. These S/N criteria are too generous if we intend to select a genuine sample of AGNs, but they may be useful to reduce the contamination of H\alpha galaxies due to AGNs.

Second, among the selected AGN host galaxies, we distinguished Seyferts from LINERs in the [O\text{III}]/H\beta versus [O\text{I}]/H\alpha diagram. We used an empirical guideline: [O\text{III}]/H\beta = 1.18 [O\text{I}]/H\alpha + 1.3, given by Kewley et al. (2000). AGN host galaxies in the LINER domain were classified as LINER galaxies, and the AGN host galaxies that are not LINER galaxies were classified as Seyfert galaxies. In other words, we classified AGN host galaxies without the signal of [O\text{I}] emission line as Seyfert galaxies in this paper.

Third, we selected as H\alpha galaxies, non-AGN galaxies with H\alpha emission with S/N \( \geq 3 \). This criterion is more generous than those in previous studies, but useful to reduce the contamination of passive galaxies due to H\alpha galaxies. Finally, passive galaxies were selected as galaxies with no or insufficient (S/N < 3) signal of H\alpha emission.

Based on the three independent classifications of galaxies, we classified the galaxies into the final 16 classes: [early-type, late-type] \times [red, blue] \times [passive, H\alpha, Seyfert, LINER]. Hereafter, we use the following abbreviations for the 16 galaxy classes: REG (red early-type galaxy), BEG (blue early-type galaxy), RLG (red late-type galaxy), BLG (blue late-type galaxy), and p- (passive), h- (H\alpha), s- (Seyfert), l- (LINER), as shown in Table 1. For example, ‘pREGs’ represents ‘passive red early-type galaxies’ and ‘sBLGs’ represents ‘Seyfert blue late-type galaxies’. Fig. 4 presents atlas images and spectra of sample galaxies in the 16 fine classes.

### Table 1. Abbreviations of the 16 fine galaxy classes

| Early-type   | Late-type   |
|--------------|-------------|
| REG          | BLG         |
| Red          | Blue        |
| Passive      | Seyfert     |
| REG          | RLG         |
| Early-type   | Late-type   |
| Red          | Blue        |
| Passive      | LINER       |
| REG          | RLG         |
| Blue         | Blue        |

3.2 Sample selection

The selection of a galaxy sample is very important, because most properties of galaxies are known to be sensitive to their luminosity and redshift. We selected three sample volumes in the luminosity versus redshift space as shown in Fig. 5. Each selected volume is a rectangle because the SDSS spectroscopy has not only a lower-brightness limit but also an upper-brightness limit for completeness. Each volume has a small redshift range and a large luminosity range, which is adequate to investigate the luminosity dependence of galaxy properties. Since our sample covers only the nearby universe (\( z < 0.1 \)), the effect of the redshift dependence is unlikely to be significant. Possible small redshift variations of galaxy properties are checked by comparing the difference between the three volumes. The V1 and V2 volumes in Fig. 5 are within the redshift range with reliable spectral information (0.04 < \( z < 0.1 \)) suggested by Kewley et al. (2004), but the V3 volume is not, implying that the spectroscopic parame-
4 OPTICAL PROPERTIES

4.1 Class composition

Table 2 lists the number of galaxies in each class and in each volume. The class composition varies with respect to the volume. The three most dominant classes are hBLGs (28.2 per cent), pREGs (14.9 per cent) and lREGs (14.1 per cent) in V1, while they are hBLGs (51.0 per cent), pREGs (7.4 per cent) and lRLGs (6.8 per cent) in V2, and hBLGs (72.8 per cent), hRLGs (5.9 per cent) and hBEGs (4.6 per cent) in V3.

Since most properties of galaxies are known to depend on their luminosity, it is necessary to study the variation of class properties with respect to their luminosity. Fig. 6 presents the class fraction versus luminosity in each volume, showing that the variation of the class fraction is continuous even between different volumes. Small discontinuities are found in several classes, but those discontinuities are not significant, considering the fractional uncertainty based on the Poisson error. These results indicate that the effect of luminosity is more important than that of redshift on the difference in the class composition between different volumes.

Choi et al. (2007) showed that the fraction of early-type...
Figure 6. Class fraction as a function of luminosity. Percentage variation of each class with respect to luminosity was derived for three volumes: V1 (open circle), V2 (open rectangle), and V3 (open triangle). Each errorbar represents the Poisson error.

galaxies decreases as luminosity decreases, which is consistent with our result. In Fig. 6, however, we found that such a trend appears to be better established between the colour classes, than between the morphology classes, among passive galaxies. In other words, passive red galaxies are dominant at the bright end, while passive blue galaxies are dominant at the faint end, on average. The class fraction distribution of HII blue galaxies is similar to that of passive blue galaxies, but the class fraction of HII red galaxies is highest at \(-20.5 \lesssim 0.1K_{\text{Bol}}(r) \lesssim -19.5\), unlike that of passive red galaxies. It is interesting that the fraction of AGN host BLGs shows decrease at the faint end, unlike that of non-AGN BLGs.

4.2 Luminosity dependence of optical properties

To understand the individual characteristics of each class, we investigate their photometric, structural, and spectroscopic properties, using seven selected physical quantities. Figs. 7 – 13 show the variation of each quantity with respect to luminosity for the 16 classes, respectively. To reduce the biases in those quantities due to internal extinction in late-type galaxies (Choi et al. 2007), late-type galaxies with axis ratio smaller than 0.6 are not used in the analysis of each physical quantity, except for axis ratio itself. To reduce the effect of abnormal data points, we use the median statistics.

Figure 7. 0.1K\((u - r)\) colour variation with respect to 0.1K\(K_{\text{Bol}}\) for each class. Each open circle shows the median value at given magnitude bin in V1, and open rectangle and open triangle do in V2 and V3, respectively. Each errorbar represents the sample inter-quartile range (SIQR) of 0.1K\(K_{\text{Bol}}\) colour at given magnitude bin. The line across symbols in each panel is the linear least-square fit.

4.2.1 Optical colour

Fig. 7 shows the luminosity dependence of 0.1K\((u - r)\) colour for each class. Nine of 16 classes have a clear trend that the fainter galaxies are bluer. Those variations are steady and continuous even in the transition ranges between volumes, implying that there is little effect from the redshift difference between volumes. pRLGs are the only class that are clearly redder when fainter, but the deviation in such a trend is somewhat large. Table 3 lists the results of linear least-squares fitting for Fig. 7. We note several interesting features in Fig. 7 and Table 3.

First, red galaxies (except for hRLGs) and HII blue galaxies show bluer colour at fainter luminosity. The colour variation in pREGs, called often the colour-magnitude relation (CMR), was explained in many previous studies. That is, the CMR of pREGs may reflect mainly the difference in the metal abundance with respect to the mass of galaxies (Kodama & Arimoto 1997; Kauffmann & Charlot 1998). The colour variation in other classes shows somewhat complicated trends, possibly affected by both age and metallicity effects. In star-forming galaxies, the fraction of young stellar population may be an important factor making the colour variation, because it is known that galaxies with small mass...
are generally young in the local universe (Bernardi et al. 2002; Treu et al. 2005).

Second, we found that pREGs and hREGs have a similar slope in their CMR within 1σ, and that the CMR slope of AGN host REGs is marginally steeper than that of pREGs. The difference in the CMR slope between different spectral classes of REGs is relatively small, compared to those of BEGs, RLGs and BLGs, showing that the metallicity effect may be dominant in REGs, irrespective of their spectral class. In other words, the effects of star formation or AGN activities may be small in REGs. The CMR slope in pREGs is about −0.09, which is significantly smaller than those in hBLGs (about −0.13). This indicates that the CMR slope of age-effect-dominated galaxies is steeper (larger colour variation) than the CMR slope of metallicity-effect-dominated galaxies, confirming the result of Choi et al. (2007).

Third, we found that AGN host galaxies in non-REG classes show very small variation in their colour. Particularly, AGN host blue galaxies do not show significant colour variation with respect to luminosity. Since galaxies with small mass are generally expected to have bluer colours than massive galaxies (Kodama & Arimoto 1997; Bernardi et al. 2002; Choi et al. 2007), such constant colours of AGN host blue galaxies are somewhat unusual. It is inferred that AGN activity may be responsible for the colour constancy, and that such AGN effects may be most prominent in blue galaxies.

Fourth, hBREGs show the largest variation in colour due to the very blue faint members of the class. The very blue faint hREGs were also identified by Choi et al. (2007), which may have much younger mean stellar ages or much poorer metal abundance than bright hREGs.

Finally, we found that pBREGs and hRLGs do not show significant variation in their colour. Since both the metallicity-magnitude relation and the age-magnitude relation are known to cause the slope in CMR, the CMR of pBREGs and hRLGs may not be the result of any single mechanism. In other words, the combined effects of age and metallicity working differentially with respect to luminosity are one possible origin of the CMR of pBREGs and hRLGs. Another possibility is differential dust extinction with respect to luminosity.

4.2.2 Colour gradient

In Fig. 3 the luminosity dependence of (g − i) colour gradient for each class is shown, and the linear fits in Fig. 3 are summarised in Table 4. As found by Choi et al. (2007), REGs have negative colour gradients (blue outside) on average, and show little variation of their colour gradients with respect to luminosity. Such a colour gradient in REGs is consistent with the previous studies, and may originate from the internal metallicity gradient (Tamura & Ohta 2003; La Barba et al. 2004). The centres of BEGs are bluer than their outer parts, which results from the shape of the domain in which early-type galaxies were selected (Fig. 1).

Choi et al. (2007) reported that the colour gradient of BEGs increases as luminosity decreases, and we additionally found

### Table 3. Slopes of the linear fits in the 0.1K(u − r) versus 0.1KE_Mottage plots

| REG     | BEG     |
|---------|---------|
| Passive | −0.087 ± 0.005(2.792) | −0.023 ± 0.018(2.426) |
| Ht      | −0.092 ± 0.004(2.776)  | −0.218 ± 0.028(2.139)  |
| Seyfert | −0.104 ± 0.006(2.771)  | −0.029 ± 0.023(2.275)  |
| LINER   | −0.104 ± 0.006(2.792)  | −0.002 ± 0.016(2.407)  |

| RLG     | BLG     |
|---------|---------|
| Passive | −0.092 ± 0.007(2.792) | 0.115 ± 0.067(1.967) |
| Ht      | −0.020 ± 0.014(2.559)  | −0.129 ± 0.007(1.810)  |
| Seyfert | −0.043 ± 0.010(2.617)  | 0.022 ± 0.016(2.110)  |
| LINER   | −0.046 ± 0.010(2.697)  | 0.020 ± 0.017(2.222)  |

The slopes of the median 0.1K(u − r) with respect to 0.1KE_Mottage, and 0.1K(u − r) at 0.1KE_Mottage(r) = −21 within parentheses.

### Table 4. As Table 3 but for Δ(g − i)

| REG     | BEG     |
|---------|---------|
| Passive | 0.004 ± 0.002(−0.028) | 0.000 ± 0.007(0.011) |
| Ht      | 0.005 ± 0.003(−0.036) | 0.050 ± 0.005(0.071) |
| Seyfert | 0.015 ± 0.009(−0.056) | 0.020 ± 0.011(0.036) |
| LINER   | 0.012 ± 0.008(−0.060) | 0.025 ± 0.014(0.026) |

| RLG     | BLG     |
|---------|---------|
| Passive | 0.018 ± 0.008(−0.063) | 0.056 ± 0.021(−0.112) |
| Ht      | 0.037 ± 0.006(−0.118) | 0.044 ± 0.002(−0.163) |
| Seyfert | 0.033 ± 0.007(−0.152) | 0.057 ± 0.004(−0.180) |
| LINER   | 0.037 ± 0.005(−0.158) | 0.055 ± 0.006(−0.184) |
that such a trend is most conspicuous in hBEGs. This implies that star formation activity in BEGs may be centrally concentrated, and that the central star formation activity in faint BEGs may be more vigorous than those in bright BEGs.

All sub-classes of late-type galaxies have negative colour gradients (i.e. bluer outside than centre) and show significantly increasing colour gradients as luminosity decreases. The increase in BLGs is slightly larger than that in RLGs. Faint late-type galaxies show very small colour difference between their centre and outside, which implies that the fraction of Scd- and Im-type galaxies in late-type galaxies may increase as luminosity decreases, as pointed out by Choi et al. (2007). It is noted that AGN host BLGs show variation in their colour gradient larger than Choi et al. (2007). It is notable that AGN host BLGs show variation in their colour gradient larger than those in bright BEGs, indicating that the star formation activity in bright hBEGs may be related to recent mergers. We found that such a trend is most conspicuous in hBEGs, indicating that the star formation activity in bright hBEGs may be related to recent mergers. It is interesting that faint hBEGs are significantly less concentrated than faint REGs, which shows a possibility that faint hBEGs may have relatively large disc components.

The concentration of late-type galaxies shows larger scatters than that of early-type galaxies, which may be partially due to the uncertainty in estimating the Petrosian radius of late-type galaxies that have typically double components (bulge+disc) in their surface profile. On average, RLGs are less concentrated than early-type galaxies, and BLGs are the least concentrated. The fact that RLGs with axis ratio > 0.6 are more concentrated than BLGs with axis ratio > 0.6 shows that the bulge fraction may be an important factor determining the colour of a late-type galaxy with small (i.e. close to face-on) inclination.

4.2.4 Axis ratio

Fig. 10 shows the luminosity dependence of axis ratio for each class. In this figure, the axis ratio cut (> 0.6) was not applied to late-type galaxies, unlike the figures for the other parameters. Table 5 summarises the linear fits in Fig. 10. It is interesting that RLGs have smaller axis ratios than BLGs on average, which may be partially due to the reddening of late-type galaxies with large inclination (Baum & Harris 2008). In other words, late-type galaxies with large inclination would be classified as RLGs, although they had blue

| Table 5. As Table 4 but for inverse concentration |
|-----------------------------------------------|
| REG          | BEG           |
| Passive      | 0.014 ± 0.003(0.325) | 0.017 ± 0.003(0.331) |
| H1           | 0.012 ± 0.002(0.330) | 0.018 ± 0.004(0.332) |
| Seyfert      | 0.015 ± 0.002(0.335) | 0.008 ± 0.003(0.344) |
| LINER        | 0.007 ± 0.002(0.329) | 0.022 ± 0.002(0.335) |

| RLG          | BLG           |
| Passive      | 0.009 ± 0.004(0.372) | −0.015 ± 0.009(0.472) |
| H1           | 0.010 ± 0.002(0.389) | 0.005 ± 0.002(0.462) |
| Seyfert      | 0.000 ± 0.004(0.393) | −0.004 ± 0.007(0.435) |
| LINER        | 0.003 ± 0.003(0.378) | −0.005 ± 0.003(0.431) |
Figure 10. The same as Fig. 7 but axis ratio as Y-axis.

Table 6. As Table 3 but for axis ratio

| REG   | BEG            |
|-------|----------------|
| Passive | $-0.007 \pm 0.006(0.744)$ | $0.002 \pm 0.021(0.677)$ |
| HII    | $-0.025 \pm 0.005(0.734)$ | $-0.016 \pm 0.011(0.734)$ |
| Seyfert | $0.003 \pm 0.018(0.678)$  | $-0.008 \pm 0.012(0.732)$ |
| LINER  | $-0.009 \pm 0.013(0.710)$ | $-0.004 \pm 0.017(0.760)$ |

Figure 11. The same as Fig. 7 but the velocity dispersion as Y-axis. The velocity dispersion was NOT corrected for the aperture effect.

Table 7. As Table 3 but for velocity dispersion

| REG   | BEG            |
|-------|----------------|
| Passive | $-44.3 \pm 1.7(166)$   | $-36.9 \pm 4.2(125)$   |
| HII    | $-43.9 \pm 2.2(158)$   | $-36.0 \pm 4.0(118)$   |
| Seyfert | $-42.1 \pm 2.6(152)$   | $-27.9 \pm 3.5(117)$   |
| LINER  | $-41.3 \pm 1.7(155)$   | $-36.6 \pm 2.8(121)$   |

colour in the face-on view. We found that the axis ratio of hREGs show significant variation with respect to luminosity, implying that faint hREGs may have larger disc components than bright hREGs, on average.

In addition to hREGs, an obvious trend that fainter galaxies have smaller axis ratio is also found in hBLGs. One possibility is that disc components may be more dominant in fainter hBLGs, because the axis ratio of galaxies with large inclination and a small bulge may appear smaller than that of galaxies with large inclination and a large bulge. However, it is also possible that this trend is caused by an inclination effect (Choi et al. 2007). In other words, since faint hBLGs are intrinsically bluer than bright BLGs (see Fig. 7), bright hBLGs with large inclination are more easily classified as hRLGs than faint hBLGs with large inclination, which makes the average axis ratio of faint hBLGs smaller than that of bright hBLGs. However, the average axis ratio of faint hRLGs is not particularly larger than that of bright hRLGs. On the contrary, faint hRLGs have marginally smaller axis ratio than bright hRLGs. This may be because hRLGs with large inclination may suffer dimming due to the extinction, causing the small average axis ratio of faint RLGs. This effect is well discussed in (Choi et al. 2007).
4.2.5 Velocity dispersion

In Fig. 11 the luminosity dependence of velocity dispersion ($\sigma_v$) for each class is displayed, and Table 8 lists the linear fits in Fig. 11. According to Fig. 11 and Table 7, early-type galaxies and red galaxies have large variations in their $\sigma_v$ with respect to luminosity, and have large median $\sigma_v$ at $0.1\alpha M_{pet}(r) = -21$, compared to late-type galaxies and blue galaxies. For example, REGs have very large variation in their $\sigma_v$ and very large median $\sigma_v$ at $0.1\alpha M_{pet}(r) = -21$, whereas BLGs have very small variation in their $\sigma_v$ and very small median $\sigma_v$ at $0.1\alpha M_{pet}(r) = -21$.

One main cause for the difference in the variation slope may be the difference in the dynamical mass profile between classes. Since the aperture size of the SDSS spectroscopy is fixed as $3''$, the $\sigma_v$ of a large galaxy reflects the small fraction of its centre, while the $\sigma_v$ of a small galaxy reflects a relatively large fraction of that galaxy. Therefore, if the dynamical mass profiles of galaxies in a class are not concentrated, the $\sigma_v = 0.1\alpha M_{pet}(r)$ relation slope in that class may be small, because the mass fraction within $3''$ aperture of a large galaxy may be much smaller than that of a small galaxy, in that class. On the other hand, the $\sigma_v = 0.1\alpha M_{pet}(r)$ relation slope in a class with a highly-concentrated dynamical mass profile, may be relatively large, because a large galaxy in that class may have relatively large fraction of its mass within $3''$ aperture.

In this sense, the large variation in $\sigma_v$ of REGs shows that their dynamical mass profiles may be highly-concentrated, and the outer parts of REGs may not significantly affect the $\sigma_v$ estimation. On the other hand, the small variation in $\sigma_v$ of BLGs indicates that their dynamical mass profiles may not be concentrated and the outer parts of BLGs may affect significantly the $\sigma_v$ estimation. However, this interpretation is cautiously suggested, because the different luminosity dependence of galaxy mass-to-light ratio between classes may also influence the difference in slope of the $\sigma_v = 0.1\alpha M_{pet}(r)$ relation. The rotation of late-type galaxies may also affect the $\sigma_v$ estimation, but late-type galaxies with small axis ratio ($<0.6$) are not used in this analysis. Therefore, the effect of late-type galaxy rotation should be relatively small.

4.2.6 Hα equivalent width

The luminosity dependence of Hα equivalent width for each class is presented in Fig. 12 and the linear fits in Fig. 12 are summarised in Table 8. A positive value of Hα equivalent width indicates line emission, and a negative value indicates line absorption. According to the definition, passive galaxies do not show any significant Hα emission. We found that red Hα galaxies (i.e. hREGs and hRLGs) show small Hα equivalent widths in the almost entire luminosity range, unlike blue Hα galaxies. The small Hα equivalent width in most red Hα galaxies implies that those galaxies have just a small fraction of current star formation.

There are trends of increasing Hα equivalent width as luminosity decreases in blue Hα galaxies, which shows that star formation activity may be more vigorous in faint galaxies, within the spectroscopic fibre aperture. Choi et al. (2007) suggested that those trends in late-type galaxies may be because the fibre spectra systematically miss the light from the outer discs of bright large galaxies, which is a possible explanation for our hBLGs sample. However, the trend in hREGs may be intrinsic rather than caused by the fibre aperture effect, because the star formation activity in hREGs may not be biased to their outer parts, as shown in Fig. 12. The trend of more vigorous star formation activity in fainter galaxies is consistent with previous studies (Bernardi et al. 2005; Treu et al. 2005), supporting the galactic downsizing scenario.

The Hα equivalent width of sBLGs shows a somewhat unusual trend: it increases from $0.1\alpha M_{pet} = -23$ to $0.1\alpha M_{pet} = -21$, but decreases from $0.1\alpha M_{pet} = -21$ to $0.1\alpha M_{pet} = -19$. In fact, the trend in sBEGs is similar to...
Figure 13. The same as Fig. 7, but the 4000 Å break index as Y-axis.

Table 9. As Table 3 but for 4000 Å break index

| Class   | REG     | BEG     |
|---------|---------|---------|
| Passive | $-0.048 \pm 0.014(1.949)$ | $-0.038 \pm 0.024(1.708)$ |
| Ht      | $-0.048 \pm 0.006(1.909)$  | $-0.072 \pm 0.017(1.438)$  |
| Seyfert | $-0.079 \pm 0.009(1.865)$  | $0.032 \pm 0.014(1.452)$   |
| LINER   | $-0.063 \pm 0.011(1.885)$  | $0.024 \pm 0.017(1.546)$   |

| Class   | REG    | BEG    |
|---------|--------|--------|
| Passive | $-0.042 \pm 0.011(1.944)$ | $0.051 \pm 0.042(1.435)$ |
| Ht      | $-0.018 \pm 0.018(1.717)$  | $-0.042 \pm 0.004(1.363)$  |
| Seyfert | $-0.044 \pm 0.009(1.769)$  | $-0.001 \pm 0.010(1.507)$  |
| LINER   | $-0.050 \pm 0.007(1.814)$  | $0.008 \pm 0.018(1.568)$   |

that in sBLGs, and is therefore possibly related to the luminosity dependence of AGN activity. However, these trends are not very significant, due to the large error bars.

4.2.7 4000Åbreak

Fig. 13 shows the luminosity dependence of the 4000Å break index for each class, and the linear fits in Fig. 13 are listed in Table 9. On average, $D_n(4000)$ of red galaxies is larger than that of blue galaxies, and $D_n(4000)$ of passive galaxies is larger than that of non-passive galaxies. Because the $D_n(4000)$ parameter reflects the fraction of old stellar population in a galaxy, this result shows that red or passive galaxies have larger mean stellar ages than blue or non-passive galaxies.

Faint REGs have smaller $D_n(4000)$ than bright REGs regardless of their spectral class, which is consistent with galaxy downsizing (Cowie et al. 1996; Treu et al. 2005), in the sense that bright (and maybe massive) galaxies have more old stellar populations than faint (and maybe less-massive) galaxies. This trend is also found in ABEGs, pRLGs, sRLGs, lRLGs and hBLGs. It is noted that blue AGN host galaxies show almost constant $D_n(4000)$ with respect to luminosity. This may be because the spectral energy distribution (SED) of those blue AGN host galaxies, within the fibre aperture, may be dominated by the AGN SED. The $D_n(4000)$ feature in hRLGs seems bimodal with large deviation, and the ARLGs in the V1 volume show a similar $D_n(4000)$ variation slope with the other RLGs.

4.3 Statistics at fixed $\sigma_v$

Since most properties of galaxies depend on each other (Bernardi et al. 2003; Choi et al. 2007), it is necessary to resample each galaxy class with the same distribution of a control parameter, for a direct comparison of galaxy properties between different classes. One of the most frequently used control parameter is luminosity, which represents basically stellar mass. However, the mass-to-light ratio of a galaxy depends on its bulge-to-disc ratio (Yoshino & Ichikawa 2008), so that luminosity is not the best as a control parameter in the studies of diverse galaxy classes. Therefore, we use velocity dispersion instead of luminosity as a control parameter, which represents galaxy dynamical mass.

Fig. 14 shows the selection of the sub-sample in each class with the same distribution of velocity dispersion. Since...
the estimation error of $\sigma_v$ is very large for $\sigma_v < 100$ km s$^{-1}$ (Choi et al. 2007), we use galaxies with $\sigma_v > 100$ km s$^{-1}$ only. Since the sample sizes of pBEGs, hBEGs, sBEGs and pBLGs are too small, their sub-samples were not selected with the same $\sigma_v$ distribution as the sub-samples of the other classes. Therefore, the results in those classes are less reliable than those in the other classes. In the sub-sample of each class, the median value and the sampling error of six physical quantities were derived as shown in Fig. 15 and Fig. 16. Each sampling error was estimated by calculating the standard deviation of the median values in 200-times-repetitive sampling. To reduce the biases in the results due to internal extinction in late-type galaxies (Choi et al. 2007), late-type galaxies with axis ratio smaller than 0.6 were not used in the analysis of each quantity, except for the axis ratio itself.

We note one possible selection bias. The velocity dispersion of each galaxy may not represent the dynamical mass perfectly, because the velocity dispersions are derived within the limited fibre aperture, and the dynamical mass profiles of galaxies in each class may not be homogeneous. Therefore, the following results may include more or less biases due to the difference in the genuine dynamical mass range of galaxies. Nevertheless, these comparisons are useful, since the velocity dispersion may at least represent the central dynamical mass of each galaxy.

A few quantities should be cautiously compared between different classes, considering the selection criteria of the classes. For example, since optical colour is one criterion to classify our sample galaxies (red galaxies versus blue galaxies), it is meaningful to compare the optical colour only in the same colour class. Similar considerations are necessary in analysing the colour gradient and light concentration.

### 4.3.1 Optical colour

REGs have similar colour regardless of their spectral class, which shows that star formation or AGN activity in REGs is not strong. In a given morphology-colour class, except for REGs, we found that H$\alpha$ galaxies are bluer than passive galaxies, and that LINER galaxies are redder than Seyfert galaxies. The trend of $0.1K (u-r)$, ‘REG > RLG > BEG > BLG’ is natural, considering the classification of morphological types in Fig. 1. It is noted that pRLGs have similar colour to that of REGs.

### 4.3.2 Colour gradient

Whereas REGs have negative colour gradients (i.e. red centres), as shown by Choi et al. (2007), BEGs have positive colour gradients (i.e. blue centres), which is consistent with previous studies (Menanteau et al. 2001; Lee et al. 2006). It is interesting that hREGs have more negative colour gradients (i.e. bluer outside) than pREGs, while hBEGs have more positive colour gradients than pBEGs. This difference implies that the process of star formation in a galaxy is different between REGs and BEGs. In other words, the star formation in an hREG may be dominant in the outer parts of the galaxy, which is possibly triggered by gas infall. On the other hand, hBEGs have star formation mainly in their centres.

We found that AGN host REGs have bluer outskirts even than aREGs, which shows a possibility that excessive gas infalling into REGs may trigger the AGN activity. No significant difference is found in the colour gradients between most spectral classes of BEGs, due to the large sampling error, except for hBEGs, which have significantly bluer centre than pBEGs, and marginally bluer centre than iBEGs.

pRLGs have very small (but still negative) colour gradients, compared to the other RLGs, showing that the disc components in pRLGs may be very small or of red colour. AGN host RLGs have larger negative colour gradients than hRLGs, which is possibly caused by the suppression of gas cooling in the centre of AGN host RLGs by AGNs. Similarly, AGN host BLGs have larger negative colour gradients than non-AGN BLGs.

### 4.3.3 Light concentration

Early-type galaxies have similar concentrations, and are more concentrated than late-type galaxies, as found by Choi et al. (2007). It is interesting that hBEGs are most concentrated among early-type galaxies, which may be due to the bright young stellar populations in the centre of ABEGs. Meanwhile, hREGs are significantly more concentrated than hBLGs, which imply that many hRLGs may be bulge-dominated late-type galaxies. It is noted that sBLGs are unusually concentrated, which may be partly due to the existence of a bright AGN in their centres.

### 4.3.4 Axis ratio

Choi et al. (2007) showed that early-type galaxies have systematically larger axis ratio than late-type galaxies, which is consistent with our results. The median axis ratio of pREGs...
5 DISCUSSION

Tables 10 summarises the median values and sampling errors of six physical quantities in the sub-samples selected with the same distribution of velocity dispersion in Fig. 13 for REGs, BEGs, RLGs, and BLGs, respectively. In the following subsections, we discuss the nature of galaxies in each fine class, mainly focusing on the results using the \( \sigma_v \)-fixed sample (153).

5.1 Red early-type galaxies (REGs)

pREGs may be typical elliptical galaxies, which are old, red and passively-evolving. Other (non-passive) REGs have similar properties to pREGs, but there are some notable differences between pREGs and non-passive REGs. First of all, hREGs have similar colour to pREGs, but their colour gradients are significantly different, in the sense that hREGs show larger negative colour gradients than pREGs. This indicates that hREGs may have blue populations in their outer parts, implying there may have been some gas infall from their outside. AGN host REGs have larger negative colour gradients even than hREGs, although the optical colour of AGN host REGs is comparable with that of pREGs.

We found that the axis ratio of AGN host REGs is significantly smaller than that of pREGs, and the axis ratio of hREGs is marginally smaller than that of pREGs. These structural features imply that the infalling gas may have formed small disc components in the outer parts of non-passive REGs. (REGs are similar to sREGs in their H\(\alpha \) equivalent width and \( D_n(4000) \), but /REGs are slightly more concentrated, implying that the disc components may be smaller in /REGs than in sREGs.

5.2 Blue early-type galaxies (BEGs)

BEGs are the galaxies in the blue tail of the early-type galaxies in the colour versus colour gradient diagram (Park & Choi 2005). BEGs have concentration index comparable to that of REGs, except for hBEGs, which are marginally more concentrated than pREGs. The axis ratios of BEGs also agree with those of REGs within very large sampling errors. These features show that BEGs are similar to REGs in their morphological structures. Compared to REGs, however, BEGs have blue colour, positive colour gradient (blue centre), large H\(\alpha \) equivalent width and small \( D_n(4000) \), indicating that BEGs have a large number of young stars, compared to REGs. Since BEGs have bluer centre than REGs, it is considered that the young stellar populations in BEGs may be concentrated toward their centre unlike typical disc galaxies, which is consistent with the previous studies about blue spheroidal galaxies.
Table 10. Summary of the median values for six parameters in each fine class

|       | pREG       | hREG       | sREG       | iREG       |
|-------|------------|------------|------------|------------|
| 0.1K(u − r) | 2.765±0.009(0.08) | 2.762±0.008(0.10) | 2.763±0.010(0.11) | 2.774±0.006(0.10) |
| Δ(g − i) | −0.034±0.003(0.03) | −0.048±0.003(0.04) | −0.065±0.004(0.04) | −0.078±0.003(0.04) |
| R50/R90 | 0.338±0.002(0.02) | 0.342±0.001(0.02) | 0.347±0.002(0.03) | 0.341±0.001(0.02) |
| Axis ratio | 0.750±0.013(0.12) | 0.720±0.011(0.14) | 0.690±0.013(0.16) | 0.710±0.010(0.15) |
| EW(Hα) [Å] | 0.169±0.011(0.12) | 0.603±0.117(0.34) | 1.226±0.148(1.02) | 1.242±0.092(0.73) |
| Dn(4000) | 1.890±0.009(0.07) | 1.861±0.008(0.08) | 1.848±0.011(0.10) | 1.831±0.008(0.09) |

|       | pBEG       | hBEG       | sBEG       | iBEG       |
|-------|------------|------------|------------|------------|
| 0.1K(u − r) | 2.484±0.073(0.06) | 2.333±0.046(0.15) | 2.287±0.040(0.12) | 2.392±0.027(0.10) |
| Δ(g − i) | −0.014±0.018(0.03) | 0.031±0.013(0.03) | 0.010±0.010(0.05) | 0.000±0.008(0.04) |
| R50/R90 | 0.329±0.010(0.01) | 0.320±0.007(0.01) | 0.338±0.006(0.02) | 0.332±0.004(0.02) |
| Axis ratio | 0.670±0.061(0.07) | 0.700±0.047(0.09) | 0.640±0.036(0.13) | 0.740±0.026(0.09) |
| EW(Hα) [Å] | 0.205±0.050(0.14) | 12.137±5.540(5.58) | 12.778±0.407(6.21) | 2.582±0.283(4.34) |
| Dn(4000) | 1.746±0.057(0.10) | 1.475±0.038(0.08) | 1.462±0.031(0.07) | 1.507±0.023(0.06) |

|       | pRLG       | hRLG       | sRLG       | iRLG       |
|-------|------------|------------|------------|------------|
| 0.1K(u − r) | 2.779±0.010(0.09) | 2.592±0.011(0.19) | 2.621±0.010(0.13) | 2.676±0.006(0.13) |
| Δ(g − i) | −0.101±0.010(0.08) | −0.171±0.006(0.07) | −0.181±0.006(0.06) | −0.190±0.003(0.06) |
| R50/R90 | 0.390±0.006(0.03) | 0.39±0.003(0.04) | 0.392±0.003(0.03) | 0.392±0.002(0.04) |
| Axis ratio | 0.700±0.024(0.12) | 0.540±0.011(0.14) | 0.600±0.009(0.14) | 0.660±0.007(0.17) |
| EW(Hα) [Å] | 0.160±0.020(0.15) | 3.565±1.059(5.16) | 2.425±0.166(2.53) | 1.687±0.097(1.05) |
| Dn(4000) | 1.917±0.021(0.06) | 1.638±0.013(0.17) | 1.759±0.011(0.13) | 1.801±0.008(0.10) |

|       | pBLG       | hBLG       | sBLG       | iBLG       |
|-------|------------|------------|------------|------------|
| 0.1K(u − r) | 2.199±0.080(0.35) | 2.008±0.017(0.17) | 2.123±0.022(0.13) | 2.248±0.022(0.14) |
| Δ(g − i) | −0.176±0.034(0.07) | −0.171±0.006(0.07) | −0.201±0.008(0.09) | −0.213±0.009(0.08) |
| R50/R90 | 0.419±0.018(0.09) | 0.41±0.004(0.05) | 0.393±0.005(0.05) | 0.411±0.005(0.03) |
| Axis ratio | 0.580±0.065(0.14) | 0.660±0.014(0.11) | 0.690±0.019(0.09) | 0.700±0.019(0.12) |
| EW(Hα) [Å] | 0.087±0.065(0.51) | 18.494±1.919(9.27) | 14.856±0.275(9.38) | 7.858±0.233(5.69) |
| Dn(4000) | 1.535±0.069(0.17) | 1.370±0.014(0.09) | 1.445±0.017(0.10) | 1.528±0.017(0.10) |

Median value ± sampling error of each parameter in the sub-samples, selected in Fig. 13. The value in the parentheses is the SIQR of each parameter in each class.

BEGs are likely to be the early-type galaxies that recently accreted cold gas from a late-type neighbour during a close encounter or merged with less significant gas-rich galaxies (Park et al. 2008).

hBEGs have a larger positive colour gradient (bluer centre) than pBEGs, whereas hREGs have a larger negative colour gradient (bluer outside) than pREGs. In other words, the star formation of hBEGs seems to be dominant in their central regions, while the star formation of hREGs seems to be dominant in their outer parts. It is noted that the structural features of hBEGs, pBEGs and pREGs are similar. The major difference between these galaxy classes is that pBEGs have bluer centres and a younger stellar population than pREGs, and that hBEGs have even bluer centres than pBEGs. However, the star formation activity in hBEGs will not continue forever, and the young stellar populations in BEGs will become older and redder as time goes on, if they do not suffer any interactions with other objects. This implies that hBEGs will probably evolve into pBEGs after their star formation ends, and that pBEGs may also evolve into pREGs much later. In other words, hBEGs, pBEGs and pREGs may form the evolutionary sequence of hBEGs → pBEGs → pREGs, as suggested by Lee et al. (2003, 2007).

The axis ratio and concentration of sBEGs are in agreement with those of sREGs, implying that Seyfert early-type galaxies may have outer disc components. However, we need to be cautious when discussing their structural similarity, because the sampling errors in BEGs are very large. iBEGs show noticeable differences from sBEGs: iBEGs have marginally larger axis ratios and marginally redder centres than sBEGs. This relationship between iBEGs and sBEGs is similar to that between iREGs and sREGs.

5.3 Red late-type galaxies (RLGs)

RLGs are bluer than REGs. Considering that the colour gradients of RLGs are significantly more negative than those of REGs, we note that what makes RLGs bluer than REGs may be the blue outer parts of RLGs (i.e. blue disc components). The existence of blue disc components in RLGs is supported by the facts that RLGs are less concentrated than early-type galaxies (for RLGs with axis ratio > 0.6) and that the axis ratios of RLGs are smaller than those of early-type galaxies. Non-passive RLGs are significantly bluer than pRLGs. The concentrations of RLGs are similar among all spectral classes.

The Dn(4000) of pRLGs agrees with that of pREGs,
but the $D_n(4000)$ of non-passive RLGs is smaller than that of non-passive REGs, and larger than that of non-passive BEGs. This indicates that the age composition of the stellar populations in RLGs may be intermediate between REGs and BEGs, except for passive galaxies. We remind the reader that these spectral features are based on the central stellar populations in each galaxy, not entire populations. The $D_n(4000)$ features of RLGs, therefore, imply that RLGs may have a larger central bulge with old stellar population, compared to BLGs. The fact that hRLGs are more concentrated than hBLGs also supports this interpretation.

The median axis ratio of RLGs (including RLGs with axis ratio $< 0.6$) is smallest among all of the colour-morphology classes, indicating that there may be many disc galaxies with large inclination within the RLGs. In other words, intrinsic BLGs with large inclination may be classified as RLGs, due to their strong dust extinction. It is noted that hRLGs have axis ratios decreasing as luminosity decreases (see Fig. 10). Intrinsically bright late-type galaxies with large inclination are dimmed due to the extinction in their discs, causing the small median axis ratio at the faint end.

$p$RLGs have significantly larger axis ratio than $h$RLGs. A good explanation for this difference is that RLGs with large inclination may be classified as $h$RLGs rather than $p$RLGs, because their disc components may be observed within the spectroscopic fibre aperture. That is, many $p$RLGs may be bulge-dominated late-type galaxies with small inclination, so that only their bulge parts were covered in the SDSS spectroscopy. However, $p$RLGs may also include genuinely passive spiral galaxies (Couch et al. 1998; Yamashita & Gotô 2001; Choi et al. 2007).

AGN host RLGs have significantly larger axis ratios than ARLGs (but smaller than $p$RLGs). This may be a selection effect caused by AGN obscuration. Since the AGN emission may be difficult to observe in disc galaxies with large inclination, the median axis ratio of the observed AGN host galaxies may be overestimated. In other words, AGN host RLGs with small axis ratio (i.e. large inclination) may be classified as $h$RLGs due to AGN obscuration.

### 5.4 Blue late-type galaxies (BLGs)

Among all colour-morphology classes, BLGs have the bluest colour, the least concentrated profile, the largest $H_\alpha$ equivalent width and the smallest $D_n(4000)$. The colour gradient of BLGs is more negative than that of RLGs, except for H$\alpha$ galaxies. Except for passive galaxies, BLGs have larger axis ratio than RLGs, which may be because intrinsic BLGs with large inclination can be classified as RLGs.

$h$BLGs may be typical late-type galaxies with a large amount of current star formation. Their blue colour (particularly in their outer parts), diffuse structure, and large $H_\alpha$ equivalent width are related to the vigorous star formation in the disc of $h$BLGs. It is difficult to find any significantly different features between $p$BLGs and $h$BLGs, due to the large sampling error of $p$BLGs, except for the $H_\alpha$ equivalent width and $D_n(4000)$. Those spectral features show that $p$BLGs may be older than $h$BLGs in their mean stellar age. Some $p$BLGs may be genuinely passive spiral galaxies.

$s$BLGs are significantly more concentrated than $h$BLGs, while the concentration of $i$BLGs is comparable with that of $h$BLGs. This is possibly due to the difference in the brightness of the central AGN between $s$BLGs and $i$BLGs. The axis ratio of AGN host BLGs is similar to that of AGN host REGs. However, the bulge-to-disc ratio of AGN host BLGs may be smaller than those of AGN host REGs, because the light profile of AGN host BLGs is much less concentrated than those of AGN host REGs. The large median axis ratio of AGN host BLGs may be due to the selection effect caused by AGN obscuration, as mentioned in §5.3.

### 6 CONCLUSIONS

We conducted a comprehensive study of the nature of the SDSS galaxies in various classes based on their morphology, colour and spectral features. Using three criteria, we classified the SDSS galaxies into early-type and late-type; red and blue; passive, H$\alpha$, Seyfert and LINER, resulting in 16 fine classes of galaxies in total. We estimated the luminosity dependence of seven physical quantities in each class, and compared the properties among classes, using a sub-sample with the same distribution of the velocity dispersion. From the analysis, we found that each galaxy class has its own distinguishable features. This shows that an analysis based on a simple classification may have a risk of mixing up different kinds of objects with different natures.

The red early-type galaxies include well-known typical elliptical galaxies ($p$REGs), but some REGs show evidence for additional star formation in their outer regions ($h$REGs). Some other REGs with AGNs ($\ast$REGs, $i$REGs) have structural properties showing the existence of larger disc components than $h$REGs, indicating the relationship between AGN activity and gas accretion. The blue early-type galaxies may be in the process of bulge formation. The structural similarity between $p$REGs, $p$BEGs and $i$BEGs supports an evolutionary sequence of $h$BEGs → $p$BEGs → $p$REGs. Seyfert early-type galaxies have a close relationship with the outer disc components of early-type galaxies, and the disc components in LINER early-type galaxies ($i$REGs, $i$BEGs) are smaller than those in Seyfert early-type galaxies, on average. The blue late-type galaxies have properties in agreement with typical spiral galaxies. Most of them are star-forming ($h$BLGs), but a very small fraction of BLGs do not show any evidence of current star formation ($p$BLGs).

Some of BLGs have an AGN ($s$BLGs, $i$BLGs), which are less detected at large inclination, and $s$BLGs show particularly bright centres on average. The median axis ratio in each class shows that some intrinsic BLGs with large inclination may often be classified as red late-type galaxies, due to strong extinction by dust in their disc. In addition to dust extinction, a large bulge-to-disc ratio may make a late-type galaxy red. Many $p$RLGs seem to be bulge-dominated late-type galaxies with small inclination, in which line emission is not detected due to the limited size of the spectroscopic fibre aperture. Like in BLGs, AGN activity is detected in some RLGs ($s$RLGs, $i$RLGs), which have small inclination.

This paper is the first in the series of comprehensive studies on the nature of the SDSS galaxies in finely-divided classes. In the following papers, we will inspect various aspects of galaxies in these classes, focusing on their multi-wavelength properties and environmental effects.
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