J. Korean Earth Sci. Soc., v. 38, no. 5, p. 333−344, September 2017
https://doi.org/10.5467/JKESS.2017.38.5.333

ISSN 1225-6692 (printed edition)
ISSN 2287-4518 (electronic edition)

Environmental Dependence of Luminosity-Size Relation of Local Galaxies

Hong Bae Ann*

Department of Earth Science Education, Pusan National University, Busan 46241, Korea

Abstract: We present the environmental dependence of the luminosity-size relation of galaxies in the local universe ($z < 0.01$) along with their dependence on galaxy morphology represented by five broad types (E, dEs, S0, Sp, and Irr). The environmental parameters we consider are the local background density and the group/cluster membership together with the clustercenteric distance for the Virgo cluster galaxies. We derive the regression coefficient (β), i.e., the slope of the line representing the least-squares fitting to the data and the Pearson correlation coefficient (c.c.) representing the goodness of the least-squares fit along with the confidence interval from bootstrap resampling. We find no significant dependence of the luminosity-size relation on galaxy morphology. However, there is a weak dependence of the luminosity-size relations on the environment of galaxies, in the sense that galaxies in the low density environment have shallower slopes than galaxies in the high density regions except for elliptical galaxies that show an opposite trend.

Keywords: galaxies: general -- galaxies: luminosity -- galaxies: size -- galaxies: structure

Introduction

There are several observable physical quantities of galaxies which are closely related to the structure of galaxies. They are luminosity, colors, size, velocity dispersion and rotational velocity. These quantities are supposed to be correlated with each other because they are related to the mass of a galaxy. Among the various correlations, the relationship between the luminosity and the size of galaxies, i.e., luminosity-size relation, is the strongest one (Giuricin et al., 1988; van den Bergh, 2008). In particular, if the Petrosian radius or the isophotal radius at a surface brightness fainter than $\mu = 25$ mag arcsec^{-2} are used as the size of a galaxy, it can replace the fundamental plane found in the elliptical galaxies (Nair et al., 2010). The tight correlation between the two is easily anticipated because both of them depend on the stellar mass of a galaxy.

Studies of the correlation between the luminosity and the size of galaxies dates back to the work of Hubble (1926) who found that this relationship depends on the morphology of galaxies. Thanks to the Sloan Digital Sky Survey (SDSS), the luminosity-size relation has been studied in a much larger sample of galaxies than those in the previous works (Blanton et al., 2003; Shen et al., 2003). The general tendency of the dependence of the luminosity-size relation on the morphology of galaxies is a faster increase of radius with luminosity in early-type galaxies which results in a small size for early type galaxies at a fixed luminosity (Shen et al., 2003). Until recently, however, most studies on the luminosity-size relation of galaxies have been carried out for bright galaxies, especially for the brightest cluster galaxies (Bernardi et al., 2007). On the other hand, dwarf galaxies are the most abundant galaxies in the universe. They are thought to be the building blocks of massive galaxies in the ΛCDM cosmology. Thus, without the understanding of dwarf galaxies, we can not comprehend the formation of galaxies.

Of particular interest in the study of the luminosity-size relation is how this relationship varies with the environment of galaxies. Earlier investigations of the luminosity-size relation gave contradictory results (Gudehus, 1973; Vader, 1986; Giuricin, 1988, 1989;

---

*Corresponding author: hbann@pusan.ac.kr
Tel: +82-51-510-2705
Fax: +82-51-513-7495

Girardi et al., 1991; Gavazzi et al., 1996; Shen, 2003). For example, Giuricin (1988) showed that the slope of the luminosity-size relation depends on the morphology and environment of galaxies in the sense that the slopes in the luminosity-size relation of lenticulars and early-type spirals in low-density environment such as the Virgo cluster are steeper than the relation for these galaxies in high-density environment such as the Coma cluster. In other words, at a given luminosity, the sizes of lenticulars and early type spirals in the Virgo cluster are smaller than those in the Coma cluster. On the other hand, Girardi et al. (1991) and Gavazzi et al. (1996) found no such dependence. For elliptical galaxies, Vader (1986) reported differences in the diameter of elliptical galaxies in the Virgo and the Coma clusters. At a given luminosity, elliptical galaxies in the Virgo cluster have smaller diameter than those in the Coma cluster whereas Giuricin (1989) reported that there are no significant difference in the luminosity-size relation in different environment.

The luminosity-size relation for dwarf galaxies, in particular its dependence on the environment is not well understood yet. Janz and Lisker (2008) showed that the size-luminosity relation of dwarf early-type galaxies in the Virgo cluster is much different from that of giant early-type galaxies. There is a weak or no dependence of size R_{eff} on luminosity (M_r) for dwarf galaxies while the size of giant early-type galaxies increases quite rapidly with their luminosities. This leads to significantly larger R_{eff} of dwarf elliptical galaxies than giant elliptical galaxies at a fixed M_r. It is not unexpected because morphological classification does not consider the size of a galaxy to determine its morphological type. Similar results, which are characterized by shallow slopes in the size -luminosity (R_{eff}-M_r) relations, were obtained for early-type dwarf galaxies of the Centaurus cluster (Misgeld et al., 2009), Antila cluster (Calderon et al., 2015) and dwarf elliptical galaxies in a range of environment (Penny et al., 2015). The shallow slope in the size-luminosity relation is not confined to the dwarf elliptical galaxies. The BCD galaxies in the Virgo cluster show a similarly shallow slope in the size-luminosity relation (Janz et al., 2014). In particular, as Penny et al. (2015) showed, the dSph galaxies in the Local Group show similarly shallow slope.

The weak dependence of size, represented by R_{eff}, on the luminosity of a galaxy, i.e., the shallow slopes in the size-luminosity relations (Janz and Lisker 2008; Misgeld et al., 2009; Calderon et al., 2015; Penny et al., 2015; Janz et al., 2017), seems to be caused by the correlation between the luminosity and Sersic index n which results in the curved relation between R_{eff} and M_r (Graham and Guzman 2003). The similarity of the slopes in the size-luminosity relation between the disk galaxies and the early-type dwarf galaxies (Kormendy 1985) seems to be due to the Sersic index n of the early-type dwarf galaxies which is close to $n = 1$. Thus, it seems better to use size parameter which is independent of the shape of luminosity profile. To do this, we consider isophotal radius similar to that used in the Second Reference Catalog of Bright galaxies (de Vaucouleurs et al. 1976; hereafter RC2) because outermost radii of galaxies seems to correlate most strongly with luminosity (Nair et al. 2010). The purpose of the present study is to understand how the luminosity-size relation depends on the morphological types and environment of galaxies using the visually classified morphological types of galaxies at $z < 0.01$ (Ann et al. 2015) and environmental measures including the local background density. We use the -band isophotal radius (R_{iso}) as the size of a galaxy to avoid the effect of the correlation between profile shape and luminosity.

This paper is organized as follows. The data and sample selection are described in section 2 and the results of the present study are given in section 3. Discussion and summary is given in the last section.

Observational Data

Morphological types of galaxies

We use the galaxies in the Catalog of Visually Classified Galaxies in the local ($z \sim 0.01$) Universe (CVCG; Ann et al., 2015). The basic source of data in the CVCG is the Korea Institute of Advanced Study

Value-Added Galaxy Catalog (KIAS-VAGC; Choi et al., 2010) which provides photometric and spectroscopic data derived from the Sloan Digital Sky Survey (SDSS) Data Release 7 (Abazajian et al., 2009). They supplemented spectroscopic redshifts of galaxies brighter than the magnitude limit of the SDSS spectroscopic observations ($r_{petrosian}\sim 14.5$) from various redshift catalogs. Ann et al. (2015) added faint galaxies from the NASA Extragalactic Data Base (NED) and the galaxies in Makarov and Karachentsev (2011) that are not overlapped with the galaxies from KIAS-VAGC. These supplements make the CVCG nearly complete to galaxies brighter than $r_{petrosian}=17.77$.

The CVCG provides the morphological types of galaxies similar to those of the third reference catalog of the bright galaxies (de Vaucouleurs et al., 1991) with some simplification for giant galaxies. Because the number of distinguished types are so large, we grouped galaxies by five broad types: E, dEs, S0, Sp, and Irr. Here, the symbol 'dEs' represents the dwarf elliptical-like galaxies which include dwarf lenticulars (dS0), dwarf ellipticals (dE), blue-cored dwarf ellipticals (dE_{bc}), blue dwarf ellipticals (dE_{blue}) and dwarf spheroidals (dSph). The frequency distribution of the five broad types of the local galaxies was presented by Ann et al. (2015). Elliptical galaxies and lenticular galaxies contribute only 1.5% and 4.9% of the local galaxies, respectively, while spiral and irregular galaxies contribute 32.1% and 42.8%, respectively. The remaining 18.7% is contributed by dEs.

Luminosity and size

We use M_r, the absolute magnitude of a galaxy in r-band, as a proxy of the luminosity of a galaxy. We derive M_r from the r-band model magnitude from the SDSS DR7. We correct the extinction by the Galaxy using the -band Galactic extinction given in the SDSS DR7. We used galaxy distances derived from the redshifts corrected for the motion relative to the centroid of the LG. If the metric distances are available from the NED, these distances were used. About 25% of galaxies have metric distances of which the majority is determined by the Tully-Fisher relation (Tully and Fisher 1977). We used H=75 km/s/Mpc. The K-correction is not applied to M_r because our sample galaxies are nearby galaxies ($z<0.01$).

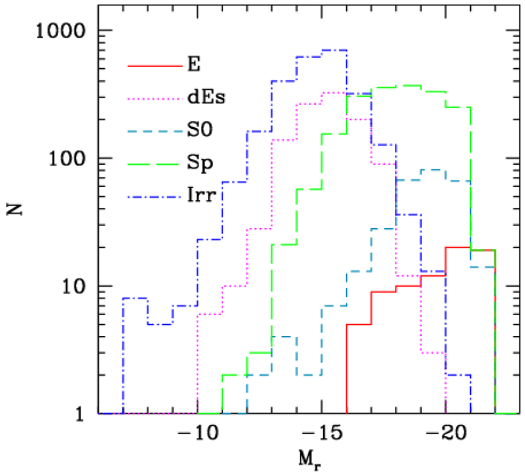

Fig. 1. Luminosity distribution of the local galaxies divided by the five broad morphological types. The types of galaxies are distinguished by line types and colors: red solid line (E), magenta dotted line (dEs), emerald short dashed line (S0), green long dashed line (Sp), and blue dot-dashed line (Irr).

Figure 1 shows the luminosity (M_r) distributions of the local galaxies divided by their broad morphological types. As shown in Fig. 1, the luminosity distributions depend on the morphological types of galaxies. They show roughly skewed Gaussian distributions with peak luminosities at bright side. Irregular galaxies and dwarf elliptical-like galaxies have the faintest peak luminosities of $M_r=-15.5$ while elliptical galaxies have the brightest peak luminosity of $M_{[r}=-20.5$. The peak luminosity of lenticular galaxies ($M_{[r}=-19.5$) is fainter than elliptical galaxies but brighter than spiral galaxies. The sharp cuts of the bright side of distributions of giant galaxies (E, Sp, and Irr) are due to the intrinsic limit on the luminosity of galaxies and the faint tail of irregular galaxies reflects the nature of the flux-limited sample. There are a number of dwarf lenticular galaxies (dS0) that are brighter than giant lenticular galaxies (S0). It is probably due to subjective nature of morphology classification by visual inspection that leads to success rate less than 90%.

We used the r-band isophotal semi-major axis given in the SDSS DR7 as the isophotal radius (R_{iso}) of a galaxy. The isophotal semi-major and semi-minor axis lengths of galaxies are measured at μ=25 mag arcsec^{-2}. We applied the internal and external extinction corrections according RC2 (de Vaucouleurs et al., 1976) as follows,

$$\log R_{iso}(kpc)=\log A_{iso}(kpc)-0.2\log(A_{iso}/B_{iso})+0.09A_G$$

where A_{iso} and B_{iso} are r-band isophotal semi-major and semi-minor axis lengths and A_G is the absorption in the r-band by the dust particles of the Galaxy.

Figure 2 shows the frequency distribution of galaxy size (R_{iso}) according to the types of galaxies. The shapes of size distributions are similar to those of the luminosity distributions, characterized by a skewed Gaussian with peak sizes at large side. As is the case of the luminosity distributions, the upper cuts in galaxy size are due to intrinsic limitation of galaxy sizes while the tails toward smaller size is due to the property of a flux-limited sample. As shown in Fig. 2, the ranges of galaxy sizes depend on the morphological types. The range of sizes of elliptical galaxies is similar to that of lenticular galaxies. Irregular galaxies and dwarf elliptical-like galaxies (dEs) have the peak size of $R_{iso}\approx$1.3 kpc while spiral and lenticular galaxies have the peak size of $R_{iso}\approx$5 kpc. There are no elliptical and lenticular galaxies larger than ~20 kpc while galaxies larger than ~50 kpc are observed in spiral galaxies. The larger size of spiral galaxies are supposed to be made by the late accretion of the cold intergalactic materials. This conjecture is supported by the large molecular gas reservoirs found in the Milky Way mass galaxies at high redshift (Papovich et al., 2016).

Results

Morphology dependence

We divide the morphological types of galaxies into five broad types (E, dEs, S0, Sp, and Irr) to see the morphological dependence of the luminosity-size relation of the local galaxies listed in the CVCG. The 'dEs' represents the dwarf elliptical-like galaxies which have five sub-types of dS0, dE, dE$_{bc}$, dSph, and dE$_{blue}$. Figure 3 shows the distribution of M_r as a function of log R_{iso} for the sample galaxies distinguished by their broad morphological types. The solid line is the least-squared solution fitted to the data sets of the M_r and R_{iso}. We applied 3 sigma clipping in the fitting process. There are tight correlations between the luminosity and size of galaxies which are well represented by

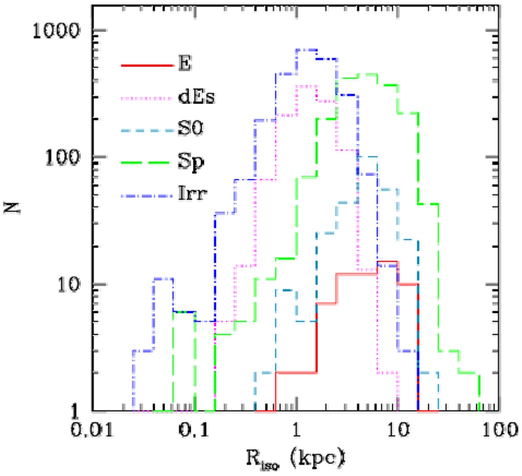

Fig. 2. Size distribution of the local galaxies divided by the five broad types.

$$M_r=\varepsilon+\beta\log R_{iso}$$

where ε and β are the intercept and regression coefficient, respectively. We derive ε and β for samples divided by their broad morphological types by the least-squares fitting method and present them in Table 1. We also present the 95% confidence interval for the regression coefficient β, calculated from 1000 bootstrap resamplings in Table 1. In the derivation of the least-squares solutions given in Table 1 we do not use data points deviated from the mean relation more than 3σ. Most of these data are spiral and irregular galaxies.

As can be seen in Fig. 3 and Table 1, the luminosity-size relations of the five broad types of galaxies are quite similar to each other. By considering

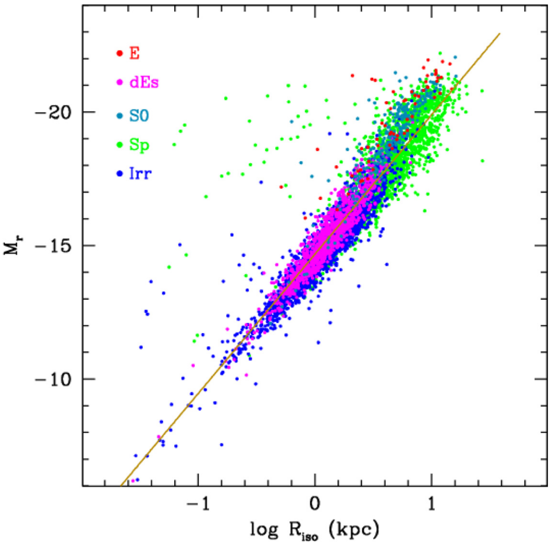

Fig. 3. Luminosity-size relation of the local galaxies. The five broad types of galaxies are distinguished by colors: red (E), magenta (dEs), emerald (S0), green (Sp), and blue (Irr). The solid line represents the least-squares solution to the observed data with 3 sigma clipping.

the 95% confidence intervals given in the 7th column of Table 1, there is no significant difference among the luminosity-size relations of the local galaxies with different morphological types.

Environmental dependence

There are a variety of ways to define the environment of a galaxy. We adopted three environment parameters to examine the dependence of the luminosity-size relation of the local galaxies ($z<0.01$). They are the local background density, the group/cluster membership, and the clustercentric distance for the galaxies in the Virgo cluster.

Local background density

The local background density of a galaxy is most widely used parameter that characterize the local environment of a galaxy. There are several ways to define the local background density of galaxies (Muldrew et al. 2012). We adopted the th nearest neighbor method to derive the local background density. Since the distances of galaxies are mostly derived from the redshifts of galaxies, they are not accurate enough to construct the three-dimensional spatial distribution of galaxies. We used the projected distances to the th nearest neighbor galaxy to calculate the local background density Σ_n. We adopted $n=5$ for the derivation of the local background density since the environmental dependence of galaxy morphology such as Hubble type and spiral arm class is well described by Σ_5 (Ann 2014). Ann et al. (2015) also used to Σ_5 explore the environment of the local galaxies.

In order to calculate Σ_5, the first thing to do is to define the neighbor galaxies from which the local background densities are derived, However, it is not trivial to define neighboring galaxies because of the large uncertainties in the galaxy distances due to the peculiar velocities that are substantial fractions of the Hubble flow for the local galaxies ($z<0.01$). In cases of using projected distances rather than spatial separations between a target galaxy and its neighbors, it is essential to assume the linking velocity (ΔV^*) that

Table 1. Correlations between M_r and R_{iso} of the local galaxies.

Type	n^a	ε	β	$c.c^b$	σ^c	CI^d
E	61	-16.79±0.24	-4.20±0.32	-0.864	0.801	-4.83,-3.41
dEs	1068	-14.68±0.02	-5.31±0.06	-0.940	0.470	-5.43,-5.19
S0	261	-15.23±0.10	-5.80±0.15	-0.932	0.626	-6.20,-5.47
Sp	1780	-14.62±0.05	-5.33±0.07	-0.876	0.833	-5.48,-5.17
Irr	2433	-14.43±0.01	-5.03±0.03	-0.950	0.491	-5.11,-4.95
All	5664	-14.67±0.02	-5.22±0.03	-0.916	0.901	-5.33,-5.11

[a] number of galaxies

[b] Pearson correlation coefficient

[c] standard deviation of the fit

[d] 95% confidence interval of β from bootstrap resampling

constrain the maximum velocity difference between a target galaxy and its neighbors. We adopted the linking velocity, $\Delta V^* = 500\ \mathrm{km\ s^{-1}}$ by considering the rms peculiar velocities of galaxies (Peebles 1979, 1987). Another parameter that should be assumed to define neighboring galaxies is the limiting luminosity (M_r*) of neighbor galaxies. Since the present sample of galaxies is a flux-limited sample, the most plausible choice of M_r* is the limiting absolute magnitude of the SDSS spectroscopic target galaxies at $z = 0.01$, i.e., $M_r = -15.2$, Using $M_r^* = -15.2$ makes our sample of background galaxies a volume-limited sample.

We calculated Σ_5 using the following equation,

$$\Sigma_5 = \frac{5}{\pi r_{p,5}^2}$$

where $r_{p,5}$ is the projected distance to the 5th nearest neighbor galaxy. We normalized Σ_5 using the mean local background density ($\overline{\Sigma_5}$) of the SDSS galaxies within $z = 0.01$ using the SDSS DR7 (Abazajian et al. 2009). In the following we used Σ' to represent the logarithm of normalized local background density, $\log(\Sigma_5/\overline{\Sigma_5})$, with the mean ($\overline{\Sigma'}$) and the standard deviation (σ).

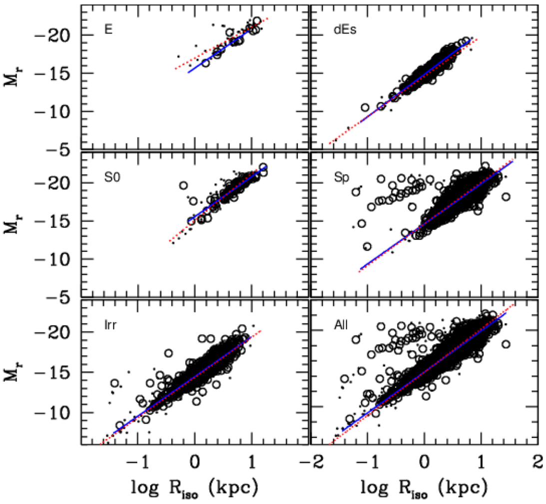

Fig. 4. Luminosity-size relations of the local galaxies with different local background densities. The solid lines represent the least-squares solutions for galaxies in the low density regions while the dotted lines represent the least-squares solutions for galaxies in the high density regions. The galaxies in the low and high density regions are represented by open circles and filled circles, respectively.

Figure 4 shows the luminosity-size relations of the five broad types of the local galaxies with regression lines for the low and high density regions. The low density regions are defined by the regions with Σ' less than $\overline{\Sigma'} - \sigma$, while the high density regions are defined by the regions with Σ' greater than $\overline{\Sigma'} + \sigma$. As can be seen in Fig. 4, there is a weak dependence of the luminosity-size relation on the local background density. However, as shown in Table 2 which summarizes the results of least-squares fittings and confidence intervals from the 1000 bootstrap resamplings, the local background density dependence of the luminosity-size relation is statistically significant for

Table 2. Correlations between M_r and R_{iso} of the local galaxies in low and high density regions

Σ^a	Type	n	ε	β	$c.c$	σ^b	CI
Low	E	13	-15.70±0.44	-5.12±0.59	-0.935	0.586	-6.13,-4.35
	dEs	298	-14.86±0.03	-5.58±0.12	-0.943	0.456	-5.85,-5.29
	S0	85	-15.56±0.16	-5.25±0.22	-0.935	0.509	-5.97,-4.54
	Sp	1042)	-14.62±0.07	-5.26±0.10	-0.855	0.844	-5.50,-5.04
	Irr	1299)	-14.49±0.02	-4.96±0.05	-0.932	0.515	-5.08,-4.83
	All	2733)	-14.57±0.02	-5.37±0.04	-0.948	0.675	-5.44,-5.30
High	E	48	-16.99±0.26	-4.06±0.35	-0.863	0.807	-4.74,-3.09
	dEs	764	-14.59±0.02	-5.27±0.07	-0.947	0.443	-5.40,-5.15
	S0	175	-15.07±0.13	-6.10±0.20	-0.921	0.667	-6.56,-5.77
	Sp	714	-14.61±0.07	-5.46±0.10	-0.898	0.815	-5.71,-5.21
	Irr	1105	-14.37±0.01	-5.02±0.04	-0.961	0.454	-5.12,-4.91
	All	2800	-14.52±0.01	-5.67±0.03	-0.960	0.642	-5.75,-5.59

[a] Local background density: Low ($>\overline{\Sigma'} - \sigma$) and High ($>\overline{\Sigma'} + \sigma$)

[b] Standard deviation of the least-squares fit.

the whole local galaxies because the low density sample has $\beta = -5.37 \pm 0.04$ with confidence interval of (−5.44, −5.30) while the high density sample has $\beta = -5.67 \pm 0.03$ with confidence interval of (−5.75, −5.59). Both of the samples have very tight correlations between the luminosity and size of galaxies with the Pearson correlation coefficients (c.c.) of ~−0.95. Although the slope difference ($\Delta\beta$) is quite small, it is statistically significant because their 95% confidence intervals do not overlap. On the other hand, if we divide the sample galaxies into sub-samples of the five broad morphological types, there is no significant differences in the luminosity-size relations of galaxies between the low density regions and high density regions. However, the case for the elliptical galaxies is very interesting because it shows an opposite trend with a large slope difference of $\Delta\beta = 1.06$. It is not clear why elliptical galaxies have a steeper slope in the low density regions, it is supposed to be originated from the difference in the formation scenario between the elliptical galaxies and others. In the current paradigm of galaxy formation in ΛCDM cosmology, major mergers of massive halos are thought to play a key role in the formation of elliptical galaxies while minor merger and accretion of sub-halos play dominant role in the formation of disk galaxies.

Galaxies in isolation, groups and clusters

We identified groups and clusters using the friends-of-friends (FOF) method (Huchra and Geller 1982). The basic parameters of the FOF are linking length (*LD*) and linking velocity (ΔV^*) which relate a target galaxy and its neighbor friend. The *LD* sets a separation limit between a target galaxy and its neighbor galaxy which can be a friend of the target galaxy while ΔV^* sets a limit of radial velocity difference between the target galaxy and its neighbor galaxy. The ΔV^* is required because the distance of a galaxy derived from the redshift is affected by its peculiar velocity. We assumed *LD* as the sum of the virial radii of target galaxy and neighbor galaxy with $\Delta V^* = 500\ \mathrm{km\ s^{-1}}$. The sum of virial radius as a linking length was used by Ann et al. (2008) and Ann (2017) to search for isolated galactic satellite systems. We assumed a neighbor galaxy is a friend of target galaxy if the projected distance between them is less than *LD* and their velocity difference is less than ΔV^*.

Since we aim to understand the effect of isolation/aggregation on the luminosity-size relation of galaxies, we divided galaxies into two sub-samples, one for isolated galaxies and the other for group/cluster galaxies. We consider isolated galaxies as the galaxies with neighbors less than three and all the others as group/cluster galaxies. There are 2352 isolated galaxies and 3319 group/cluster galaxies including the galaxies in the Virgo cluster. Some of them were not used in the derivation of the regression coefficients because of large deviations from the mean lines.

Table 3. Correlations between M_r and R_{iso} of the local galaxies in isolated and group/cluster environment.

env[a]	Type	*n*	ε	β	*c.c*	σ^b	*CI*
Field	E	6	-15.27±0.22	-5.79±0.30	-0.995	0.266	-6.45,-5.30
	dEs	295	-14.88±0.03	-5.59±0.10	-0.958	0.456	-5.84,-5.33
	S0	42	-16.18±0.31	-4.27±0.49	-0.812	0.947	-6.25,-2.43
	Sp	725	-14.48±0.07	-5.33±0.11	-0.879	0.758	-5.53,-5.10
	Irr	1247	-14.44±0.02	-5.04±0.05	-0.947	0.505	-5.15,-4.94
	All	2313	-14.53±0.02	-5.27±0.03	-0.955	0.619	-5.34,-5.20
Group	E	56	-17.18±0.28	-3.76±0.38	-0.807	0.890	-4.53,-2.90
	dEs	773	-14.60±0.02	-5.32±0.07	-0.937	0.449	-5.47,-5.17
	S0	222	-15.33±0.16	-5.69±0.18	-0.904	0.694	-6.24,-5.25
	Sp	1054	-14.74±0.06	-5.30±0.09	-0.877	0.863	-5.51,-5.10
	Irr	1186	-14.42±0.01	-5.02±0.05	-0.953	0.475	-5.13,-4.14
	All	3280	-14.53±0.02	-5.66±0.03	-0.955	0.681	-5.73,-5.58

[a] Galaxy environment divided into field and group/cluster.
[b] Standard deviation of the least-squares fit.

Figure 5 shows the luminosity-size relations of galaxies divided by group/cluster membership. The general trend of environmental dependence of luminosity-size relations of the local galaxies is the same as that found in Fig. 4 where we consider the local background density as a measure of galaxy environment. That is, the luminosity-size relations of galaxies in the low density environment (i.e, galaxies in isolation) show shallower slopes than those for the high density environment (i.e., galaxies in groups and clusters). This dependence of the luminosity-size relation on the group/cluster membership is statistically significant because their 95% confidence intervals do not overlap. The opposite trend observed in the elliptical galaxies is also statistically significant.

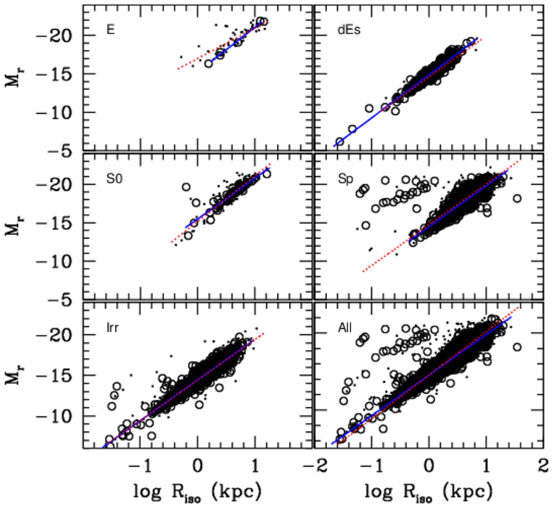

Fig. 5. Luminosity-size relations of the local galaxies in different group environment. The solid and dotted lines represent the least-squares solutions for the isolated galaxies and group/cluster galaxies, respectively.

Clustercentric distance

It is of interest to see whether the luminosity-size relation depends on local environment or global environment. The local environment of a galaxy can be easily defined by a variety of ways, regardless of being field galaxy or cluster galaxy. One of the measures of local environment is the local background density such as those used in the current study. The global environment of a galaxy also can be defined by several ways but the clustercentric distance is a good measure of global environment that is found to be correlated with galaxy morphology fractions (Whitmore and Gilmore 1991; Whitmore et al., 1993). Whitmore et al. (1993) reported that morphology-clustercentric distance relation is more fundamental than morphology-density relation (Dressler 1980) from the reanalysis of the 55 cluster data of Dressler (1980).

We divide the galaxies in the Virgo cluster into two sub-samples, inner regions and outer regions, using the projected distances from M87. The dividing distance (1.6 Mpc) is the mean projected distance of the cluster galaxies from M87. We compare the luminosity-size relations of the inner regions with those of the outer

Table 4. Correlations between M_r and R_{iso} of the Virgo cluster galaxies

r_p^a	Type	n	ε	β	$c.c$	σ^b	CI
<1.6	E	18	-17.44±0.53	-3.49±0.90	-0.695	1.300	-4.60,-2.01
	dEs	295	-14.38±0.04	-5.08±0.14	-0.905	0.503	-5.38,-4.73
	S0	46	-15.39±0.42	-5.24±0.62	-0.787	0.725	-7.40,-4.08
	Sp	120	-15.62±0.27	-3.87±0.34	-0.723	0.937	-4.71,-3.07
	Irr	153	-14.11±0.05	-4.64±0.18	-0.903	0.507	-5.07,-4.16
	All	626	-14.30±0.04	-5.56±0.09	-0.928	0.734	-5.77,-5.33
>1.6	E	5	-15.95±0.81	-5.07±1.15	-0.931	0.884	-6.92,-1.31
	dEs	126	-14.39±0.05	-5.41±0.16	-0.949	0.445	-5.64,-5.17
	S0	36	-15.16±0.38	-5.29±0.53	-0.866	0.888	-6.72,-4.54
	Sp	118	-14.58±0.21	-4.81±0.27	-0.857	0.913	-5.39,-4.23
	Irr	144	-14.14±0.06	-4.97±0.19	-0.911	0.557	-5.46,-4.51
	All	426	-14.29±0.05	-5.39±0.09	-0.944	0.708	-5.60,-5.16

[a] Projected distance (Mpc) from M 87. The division of 1.6 Mpc is the mean projected separation.
[b] Standard deviation of the least-squares fit.

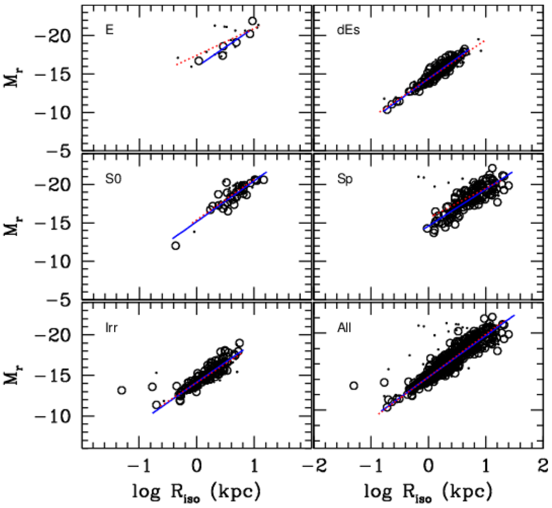

Fig. 6. Luminosity-size relations of the galaxies in the Virgo cluster. The best fit regression lines for the inner regions are plotted by the dotted lines and those for the outer regions are represented by the solid lines, respectively.

regions for the five sub-samples divided by their broad morphological types. The galaxies in the inner regions are assumed to be completely virialized while those in the outer regions are assumed to include new comers including spiral galaxies falling into the Virgo cluster recently (Tully and Shaya 1984).

Figure 6 shows the luminosity-size relations for the galaxies in the Virgo cluster divided by the locations within the Virgo cluster. There is no difference between the galaxies in the inner regions and those of the outer regions except for the elliptical galaxies that show shallower slope for the ellipticals in the inner regions of the Virgo cluster. Our result is consistent with that of Giuricin et al. (1988) who analyzed the luminosity-size relations for galaxies in the inner and outer regions of the Virgo cluster. We summarize the results of the least-squares fittings in Table 4.

Summary and Discussion

We have analyzed the dependence of the luminosity-size relations of galaxies on their morphology and environment using the morphological types of Ann et al. (2015) and photometric data from the SDSS DR7. The majority of the redshift data came from the SDSS DR7, but the redshifts of bright galaxies which were not the target galaxies of SDSS spectroscopic observation were obtained from the NED. We used the absolute magnitude in the r-band model magnitude M_r for the proxy of the galaxy luminosity and r-band isophotal semi-major axis, R_{iso} measured at μ_r=25 mag arcsec^{-2} corrected for the extinction in the Galaxy and the internal extinction by the prescription introduced in the RC2. The basic statistical methods we applied are the least-squares fitting and the bootstrap resamplings.

We divided the sample galaxies into five broad types (E, dEs, S0, Sp, and Irr) to see the morphology dependence of the luminosity-size relation of the local galaxies. The dwarf elliptical-like galaxies (dEs) consist of five sub-types of dS0, dE, $\mathrm{dE_{bc}}$, dSph, and $\mathrm{dE_{blue}}$. We derived the regression coefficients and confidence intervals of the correlation between M_r and R_{iso} by least-squares fitting technique and bootstrap resampling with 1000 bootstrap samples. There is no appreciable difference in the regression coefficients of the luminosity-size relations for galaxies with five broad morphological types. The mean regression coefficient is −5.22±0.03 with 95% confidence interval of (−5.33, −5.11). The steepest slope was observed in the luminosity-size relations of S0 galaxies (−5.80±0.15) while the shallowest slope was derived for E galaxies (4.20±0.32). The Pearson correlation coefficient (c.c) for the mean relation is −0.916 and they are roughly the same for other morphological types.

We have explored the environmental dependence of the luminosity-size relation of the local galaxies using three environment parameters: local background density, group/cluster membership and cluster-centric radius. We found that the slopes of the luminosity-size relations in low density environment, i.e., isolated galaxies, galaxies with low local background density, and galaxies in the outer skirts of the Virgo cluster, are shallower than those for galaxies in high density environment except for elliptical galaxies that show an opposite trend. The differences in the slopes of the luminosity-size relations among different environment seem to be statistically significant because the regression coefficient (i.e., slope) of the low density regions is $\beta = -5.37 \pm 0.04$ with 95% confidence interval (CI) of (−5.44, −5.30) while $\beta = -5.67 \pm 0.03$ and CI=(−5.75, −5.59) for the high density regions. For the case of the environment parameters representing degree of isolation, we found similarly significant differences in the slopes of the luminosity-size relations between the isolated galaxies and the group/cluster galaxies. They have $\beta = -5.27 \pm 0.03$ with CI of (−5.34, −5.20) for the isolated galaxies and $\beta = -5.66 \pm 0.03$ with CI of (−5.73, −5.58) for the group/cluster galaxies. Most pronounced differences were observed for S0 galaxies but they are not statistically significant due to large errors, Since formation of S0 galaxies is supposed to be different according to their environment, analysis of the luminosity-size relation for a large sample of S0 galaxies may provide some clues to understand the formation of S0 galaxies. On the other hand, there is no significant difference in the slopes of the luminosity-size relations between the galaxies in the inner regions and those in the outer skirts of the Virgo cluster. The opposite trend observed for elliptical galaxies is also observed for the two samples of the Virgo cluster galaxies but the difference is not as large as those for the galaxies divided by the local background density or degree of isolation.

How can we understand the observed dependence of regression coefficient between the luminosity and size of galaxies on the environment. It has shallower slopes for isolated galaxies in low density regions or in the outer skirts of cluster than the group/cluster galaxies in high density regions or in the inner region of cluster. In most cases, a larger luminosity difference is observed in the small-sized galaxies. At fixed size, the luminosities of galaxies in the low density environment are brighter than those in the high density environment except for elliptical galaxies. Thus, a shallow slope means a slow increase in luminosity with increasing galaxy size in the low density environment. Since size growth is mainly achieved by minor mergers of sub-halos with stellar component or star formation in the cold gas accreted, it suggests that high density environment provides favorable conditions for the growth of galaxy luminosities. It is not clear why elliptical galaxies show opposite trend of the dependence of regression coefficients on the environment measures. It could be caused by heterogeneous sample of elliptical galaxies including elliptical galaxies with significant merger signature as well as compact elliptical galaxies. But if we consider that shallow slope leads to brighter luminosity at small radius, elliptical galaxies in the high density environment is brighter than those in the low density environment to keep compact structures to survive from the tidal perturbations which are expected to be strong in the high density regions. It is of interest to note that our profile independent measure of the galaxy size (isophotal radius) gives rise to an information on the luminosity profile of a galaxy through the luminosity-size relation.

Acknowledgments

This work was supported by a 2-Year Research Grant of Pusan National University.

References

Abazajian, K.N. et al., 2009, The Seventh Data Release of the Sloan Digital Sky Survey, The Astrophysical Journal Supplement Series, 182, 543-558.

Ann, H.B., Park, C., and Choi, Y.-Y., 2008, Galactic satellite systems: radial distribution and environment dependence of galaxy morphology, Monthly Notices of the Royal Astronomical Society, 389, 86-92.

Ann, H.B., 2014, Environment Dependence of Disk Morphology of Spiral Galaxies, Journal of the Korean Astronomical Society, 47, 1-13.

Ann, H.B., Seo, M., and Ha, D. K., 2015, A Catalog of Visually Classified Galaxies in the Local (z~0.01) Universe, The Astrophysical Journal Supplement Series, 217, 27-49.

Ann, H.B., 2017, Morphology of Dwarf Galaxies in Isolated Satellite Systems, Journal of the Korean Astronomical Society, Journal of the Korean Astronomical Society, 50, 111-124.

Bernardi, M., Hyde, J.B., Sheth, R.K., Miller, C.J., and Nichol, R.C., 2007,The Luminosities, Sizes, and Velocity Dispersions of Brightest Cluster Galaxies: Implications for Formation History, The Astronomical

Journal, 133, 1741-1755.

Blanton, M.R. et al., 2003, The Galaxy Luminosity Function and Luminosity Density at Redshift z=0.1, The Astrophysical Journal, 592, 819-838.

Caldern, J.P., Bassino, L.P., Cellone, S.A., Richtler, T., Caso, J.P., and Gmez, M., 2015, Early-type galaxies in the Antlia Cluster: a deep look into scaling relations, Monthly Notices of the Royal Astronomical Society, 451, 791-803.

Choi, Y.-Y., Han, D.-H., and Kim, Sungsoo S., 2010, Korea Institute for Advanced Study Value-Added Galaxy Catalog, Journal of the Korean Astronomical Society, 43,191-200.

de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H.G., 1976, Second Reference Catalogue of Bright Galaxiess (Austin: Univ. Texas, Austin).

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Buta, R.J., Paturel, G., and Fouque, P., 1991, Third Reference Catalogue of Bright Galaxies, Vol. 1-3 (New York: Springer).

Dressler, A., 1980, Galaxy morphology in rich clusters-Implications for the formation and evolution of galaxies, The Astrophysical Journal, 236, 351-365.

Gavazzi, G., Pierini, D., and Boselli, A., 1996, The phenomenology of disk galaxies. Astronomy and Astrophysics, 312, 397-408.

Girardi, M., Biviano, A., Giuricin, G., Mardirossian, F., and Mezzetti, M., 1991, The luminosity-diameter relation for disk galaxies in different environments, The Astrophysical Journal, 366, 393-404.

Giuricin, G., Mardirossian, F., and Mezzetti, M., 1988, he luminosity-diameter relationship of disk galaxies in clusters, Astronomy and Astrophysics Supplement Series, 72, 151-161.

Giuricin, G., Mardirossian, F., Mezzetti, M., and Pisani, A., 1989, The luminosity-diameter relations of elliptical galaxies in different environments, The Astrophysical Journal, 345, 101-107.

Graham, A.W. and Guzman, R., 2003, HST Photometry of Dwarf Elliptical Galaxies in Coma, and an Explanation for the Alleged Structural Dichotomy between Dwarf and Bright Elliptical Galaxies, The Astronomical Journal, 125, 2936-2950.

Gudehus, D.H., 1973, Radius-parameter and surface brightness as a function of galaxy total magnitude for clusters of galaxies. The Astronomical Journal, 78, 583-593.

Hubble, E.P., 1926, Extragalactic nebulae, The Astrophysical Journal, 64, 321-369.

Huchra, J.P. and Geller, M.J., 1982, Groups of galaxies. I-Nearby groups, The Astrophysical Journal, 257, 423-437.

Janz, J. and Lisker, T., 2008, The Sizes of Early-Type Galaxies, The Astrophysical Journal Letter, 689, L25-L28.

Janz, J. et al,, 2014, A Near-infrared Census of the Multicomponent Stellar Structure of Early-type Dwarf Galaxies in the Virgo Cluster, The Astrophysical Journal, 786, 105-137.

Janz, J., Penny, S.J., Graham, A.W., Forbes, D.A., and Davies, R.L., 2017, Implications for the origin of early-type dwarf galaxies-the discovery of rotation in isolated, low-mass early-type galaxies, Monthly Notices of the Royal Astronomical Society, 468, 2850-2864.

Kormendy, J., 1985, Families of ellipsoidal stellar systems and the formation of dwarf elliptical galaxies, The Astrophysical Journal, 295, 73-79,

Makarov, D. and Karachentsev, I., 2011, Galaxy groups and clouds in the local (z~0.01) Universe, Monthly Notices of the Royal Astronomical Society, 422, 2498-2520.

Misgeld, I., Hilker, M., and Mieske, S., 2009, The early-type dwarf galaxy population of the Centaurus cluster, Astronomy & Astrophys, 496, 683-693.

Muldrew, S.I., et al., 2012, Measures of galaxy environment-I. What is ‘environment’?, Monthly Notices of the Royal Astronomical Society, 419, 2670-2682.

Nair, P.B., van den Bergh, S., and Abraham, R.G., 2010, The Environmental Dependence of the Luminosity-Size Relation for Galaxies, The Astrophysical Journal, 715, 606-622.

Papovich, C. et al., 2016, Large molecular gas reservoirs in ancestors of Milky Way-mass galaxies nine billion years ago, Nature Astronomy, 1, 3-12.

Peebles, P.J.E., 1979, The mean mass density estimated from the Kirshner, Oemler, Schechter galaxy redshift sample, The Astronomical Journal, 84, 730-734.

Peebles, P.J.E., 1987, Origin of the large-scale galaxy peculiar velocity field-A minimal isocurvature model, Nature, 327, 210-211.

Penny, S.J., Janz, J., Forbes, D.A., Benson, A.J., and Mould, J., 2015, The scaling relations of early-type dwarf galaxies across a range of environments, Monthly Notices of the Royal Astronomical Society, 453, 3635-3648.

Shen, S., Mo, H.J., White, S.D.M., Blanton, M.R., Kauffmann, G., Voges, W., Brinkmann, J., and Csabai, I., 2003, The size distribution of galaxies in the Sloan Digital Sky Survey, Monthly Notices of the Royal Astronomical Society, 343, 978-994.

Tully, R.B. and Fisher, J.R., 1977, A new method of determining distances to galaxies, Astronomy and Astrophysics, 54, 661-673.

Tully, R.B. and Shaya, E.J., 1984, Infall of galaxies into the Virgo cluster and some cosmological constraints, The Astrophysical Journal, 281, 31-55.

van den Bergh, S., 2008, Astrophysics: How do galaxies form? Nature, 455, 1049-1051.

Vader, J.P., 1986, Multivariate analysis of elliptical galaxies in different environments, The Astrophysical Journal, 306, 390-400.

Whitmore, B.C. and Gilmore, D.M., 1991, On the interpretation of the morphology-density relation for galaxies in clusters, The Astrophysical Journal, 367, 64-68.

Whitmore, B.C., Gilmore, D.M., and Jones, C., 1993, What determines the morphological fractions in clusters of galaxies? The Astrophysical Journal, 407, 489-509.

Manuscript received: August 3, 2017
Revised manuscript received: September 7, 2017
Manuscript accepted: September 22, 2017