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# DIFFERENCES IN THE LUMINOSITY FUNCTIONS OF FAINT EARLY-TYPE AND FAINT LATE-TYPE GALAXIES IN FOUR NEARBY CLUSTERS OF GALAXIES[1]

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## ABSTRACT

We have carried out a photometric survey of four nearby clusters of galaxies, A1656, A1367, A1644, and A1631, with mosaic CCD cameras. The observed luminosity functions of A1656, A1367, and A1631 cannot be approximated by the Schechter function with $\alpha = -1.25$ over the whole magnitude range $-21.5 \leq M_R \leq -16.0$, although the bright parts ($M_R \leq -18$) have a Schechter form in all of the four clusters. The luminosity functions of late-type galaxies have a similar shape for all the clusters, while those of faint early-type galaxies ($M_R \geq -18$) show a large variation from cluster to cluster. Only A1644 lacks the faint early-type galaxies, and its luminosity function is in the Schechter form over all of the magnitude range observed.

*Subject headings:* galaxies: clusters: individual (A1656, A1367, A1631, A1644) — galaxies: luminosity function, mass function

## 1. INTRODUCTION

The luminosity function (LF) of galaxies plays an important role in understanding the formation and evolution of structures in the universe (see, e.g., review by Binggeli, Sandage, & Tammann 1988). Several studies of LFs of rich clusters (e.g., Lugger 1986; Colless 1989) favor the universality of the cluster total LF, which is well fitted to the Schechter function (Schechter 1976). However, most of such studies, which are based on photographic plates, are limited to only the bright end ($M_R < -18$). It is only for three clusters, Virgo (Sandage, Binggeli, & Tammann 1985, hereafter SBT), Fornax (Ferguson & Sandage 1988), and Coma (Thompson & Gregory 1993, hereafter TG), that photographic observations yielded both a deeper limiting magnitude ($M_R \sim -13$) and good resolution for morphological classification, which are critical for detailed LF studies. Cluster LFs down to the very faint end ($M_R < -11$) have been obtained only recently for several clusters (De Propris et al. 1995; Bernstein et al. 1995), but they are obtained in quite narrow core regions covered by a single CCD.

In this Letter we present the LFs of early- and late-type galaxies as well as the total LF in four clusters based on large homogeneous samples with a faint limiting magnitude ($M_R \sim -16$). Such samples are made available by three new techniques; the CCD mosaic, semiautomated data reduction/analysis software, and the quantitative and objective classification of morphological types of galaxies based on surface photometry parameters.

## 2. OBSERVATIONS AND DATA REDUCTIONS

Observations were made with two mosaic CCD cameras in the $R$ ($\lambda_{\rm eff} \sim 670$ nm) band. The first CCD camera (hereafter MCCD1) consists of an $8 \times 2$ array of $1000 \times 1018$ pixel CCDs (Sekiguchi et al. 1992), and the second one (hereafter MCCD2) consists of a $7 \times 4$ array of the same CCDs (Kashikawa et al. 1995). In our mosaic CCD cameras, CCDs are placed with a relatively large space between the chips. One contiguous field is completed by taking several exposures, each shifted by a fixed amount on the CCD grid. The pixel size is 12 $\mu$m square. The exposure time was 20 minutes.

A1656 (Coma) and A1367 were observed on 1992 May 1–2 and 1993 March 17–21 with MCCD1 attached to the prime focus of the 105 cm Schmidt telescope at the Kiso Observatory. The image scale is 0.″75 pixel$^{-1}$. The observed field for each cluster, $1.°7 \times 3.°4 = 5.3$ deg$^2$, was covered by 15 exposures. The seeing size was 4.″5 FWHM on the average. A1644 and A1631 were observed on 1994 May 2–11 with MCCD2 attached to the Cassegrain focus of the 40 inch (1 m) Swope telescope at the Las Campanas Observatory. The image scale is 0.″35 pixel$^{-1}$. The observed field for each cluster, $0.°70 \times 1.°22 = 0.83$ deg$^2$, was covered by four exposures. The average seeing size was 1.″5 FWHM.

The data reduction is essentially the same for both MCCD1 and MCCD2. Each frame is bias-subtracted and flat-fielded separately, followed by sky background subtraction. The most important process is the frame mosaicking, where a common flux scale and a common coordinate system are established over a contiguous field using the stars in the overlapped regions of neighboring frames. In the case of A1656, for example, the magnitude error at $17.5 < m_R \leq 18.0$ is 0.08 mag (rms). We detect objects and measure photometric parameters simultaneously after the frame mosaicking. All objects are detected which exceed the local sky by more than 1.5 $\sigma$ and have more connected pixels than $N_{\rm pix}^{\rm min}$, which corresponds to FWHM of the stellar image. Therefore, the magnitude we use in this study is the isophotal magnitude at the threshold surface brightness listed in Table 1. The photometric zero point is determined using photometric standard stars. We adopt the Galactic absorption correction $A_R = 0.61\ A_B$, with $A_B$ given by Burstein & Heiles (1984). The internal absorption

[1] Based on observations at the Kiso Observatory and the Las Campanas Observatory.



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TABLE 1

SAMPLES OF CLUSTERS OF GALAXIES

| Cluster | $N$ [a] | | | SA [b] | $M_R^{\rm lim}$ [c] | $\mu_{\rm th}$ [d] | $\bar{v}$ [e] | $\sigma$ [f] |
|---|---|---|---|---|---|---|---|---|
| | Total | Early | Late | (deg$^2$) | (mag) | (mag arcsec$^{-2}$) | (km s$^{-1}$) | (km s$^{-1}$) |
| A1656 .......... | 1822 | 1313 | 509 | 5.25 | −16.0 | 24.23 | 6942 | 1140 |
| A1367 .......... | 1157 | 799 | 358 | 5.27 | −16.0 | 24.46 | 6464 | 802 |
| A1644 .......... | 1019 | 231 | 788 | 0.82 | −16.5 | 23.99 | 14213 | 939 |
| A1631 .......... | 884 | 405 | 479 | 0.83 | −16.0 | 24.15 | 13958 | 628 |

[a] Number of sample galaxies.
[b] Survey area.
[c] Limiting magnitude.
[d] Threshold surface brightness.
[e] Mean velocity.
[f] Velocity dispersion.

is corrected following the method given in RC3 (de Vaucouleurs et al. 1991).

## 3. SAMPLE SELECTION

We take a parameter log ($I_{\rm peak}/N_{\rm pix}$) as a star/galaxy discriminator, where $I_{\rm peak}$ is the peak count of an object and $N_{\rm pix}$ is the number of connected pixels in the object. We define by eye inspection the boundary line between stars and galaxies on the plane of log ($I_{\rm peak}/N_{\rm pix}$) versus magnitude, where stars form a well-defined sequence which is separated from the distribution of galaxies. The observed star count based on the boundary line shows very good agreement with the prediction of the Yamagata & Yoshii (1992) model for all of the four cluster regions down to $m_R \sim 18.5$ (A1656 and A1367) and $m_R \sim 20.0$ (A1644 and A1631) depending on the seeing size.

The number of field galaxies at a given magnitude and at a given $z$, $n(m, z)$, is computed by multiplying the field LF with the comoving volume. The field LF we adopt here is that of the AARS survey (Peterson et al. 1986), derived by Efstathiou, Ellis, & Peterson (1988). We assume that there are very few galaxies in front of a cluster, as several spectroscopic studies show (e.g., Fig. 3 of Kirshner et al. 1987). We estimate the number of field galaxies by integrating $n(m, z)$ in the redshift space from a threshold to infinity, instead of from zero to infinity as is usually assumed for a uniform distribution. The threshold is taken to be 1 $\sigma$ above the mean cluster velocity, where $\sigma$ is the velocity dispersion of the cluster. The velocity data are taken from Zabludoff, Geller, & Huchra (1993) and Dressler & Shectman (1988) and are given in Table 1.

We classify the sample galaxies into two broad classes, early and late types, based on the surface brightness profile. Early-type galaxies show a de Vaucouleurs law profile, which has a higher central concentration than the exponential profile of late-type galaxies. The definition of the central concentration index $C_{\rm in}$ and the concept of this classification method are described in Doi, Fukugita, & Okamura (1993). We compute $C_{\rm in}$ for two series of model galaxies. For each observed galaxy, an early-type model with a de Vaucouleurs law profile, and a late-type model with the exponential profile, are generated so that they have the same magnitude, surface brightness, and axis ratio as the galaxy. The model galaxies are smeared with a single Gaussian with the observed seeing size. For each galaxy, we define the critical value $C_{\rm in}^{\rm crit}$ as

$$C_{\rm in}^{\rm crit} = C_{\rm in}^S + p(C_{\rm in}^E - C_{\rm in}^S), \quad (1)$$

where $C_{\rm in}^E$ and $C_{\rm in}^S$ are the values of $C_{\rm in}$ of the early-type model and the late-type model, respectively, and $p$ is the free parameter ($0 \leq p \leq 1$). A galaxy is classified as early (late) type when it has $C_{\rm in}$ larger (smaller) than $C_{\rm in}^{\rm crit}$. We determine the parameter $p$ empirically, based on the bright galaxies in Dressler's (1980) sample using his classification as fiducial. We choose $p = 0.35$, which gives the same completeness to both the early-type sample and the late-type sample according to Dressler's classification. The $p$-value is common for all the cluster samples because $C_{\rm in}$ is a distance-independent parameter.

Table 1 summarizes the characteristics of our samples. The LFs are derived down to the faint end $M_R = -16$ ($M_R = -16.5$ for A1644), limited by the accuracy of star/galaxy discrimination.

## 4. RESULTS AND DISCUSSION

Apparent magnitudes are converted to absolute magnitudes using the distance moduli of the clusters computed with the mean cluster velocities given in Table 1. We assume $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$. Figure 1 shows the differential total (early-type + late-type) LFs of the four clusters with 0.5 mag bins. The LFs with the field correction are shown by filled circles with statistical 1 $\sigma$ error bars, while those without the field correction are shown by open squares.

The field-corrected LF is fitted to the Schechter function (Schechter 1976), which is in the form

$$N(M)dM = kN^* \exp\{[-k(\alpha+1)(M-M^*)] - \exp[-k(M-M^*)]\}dM, \quad (2)$$

where $N(M)$ is the number density; $M$ is the absolute magnitude; $N^*$, $\alpha$, and $M^*$ are the fitting parameters; and $k \equiv (\ln 10)/2.5$. The $\chi^2$ statistic is minimized with respect to the two parameters ($N^*$, $M^*$) with $\alpha$ fixed at −1.25, which is the value obtained by Schechter (1976), Lugger (1986), and Colless (1988). The $\chi^2$ defined here includes the uncertainty (both the statistical error and the systematic error) of the field correction (Lugger 1986). Some of the brightest galaxies are omitted because of the saturation. Hence, the brightest bin, $-22 < M_R \leq -21.5$, is excluded in the fit. The fits are made over the whole magnitude range ($M_R \geq -21.5$) and in the bright part ($-21.5 \leq M_R \leq -18$) separately. The result is shown in Figure 1 by the solid line for the whole magnitude range and by the dotted line for the bright part. Table 2 lists the parameters $N^*$ and $M^*$ obtained in this two-parameter fit, together with $P(\chi^2|\nu)$, the probability of the $\chi^2$ fit. The bright

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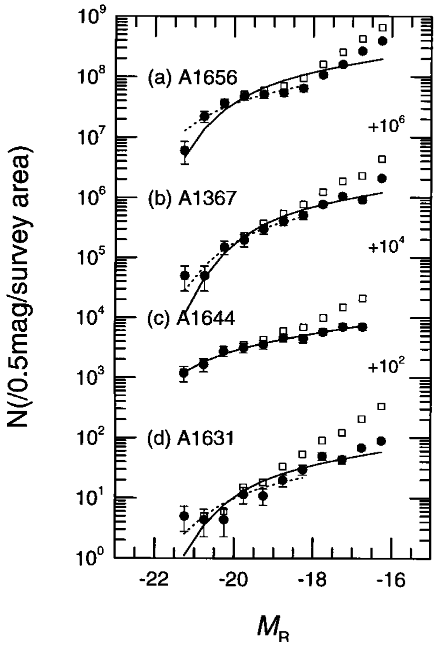


FIG. 1.—Luminosity function (LF) for the total sample of each cluster. (*a*) A1656 (curves and symbols are shifted along the ordinate by $\Delta N = 10^6$); (*b*) A1367 ($\Delta N = 10^4$); (*c*) A1644 ($\Delta N = 10^2$); (*d*) A1631. The LF with field correction is indicated by filled circles, and open squares indicate the LF without field correction. The error bars are 1 $\sigma$ statistical fluctuations. The best two-parameter fit of the Schechter function with fixed $\alpha$ at $-1.25$ is denoted by the solid line for the whole magnitude range ($M_R \geq -21.5$) and by the dotted line for the bright part ($-21.5 \leq M_R \leq -18$).

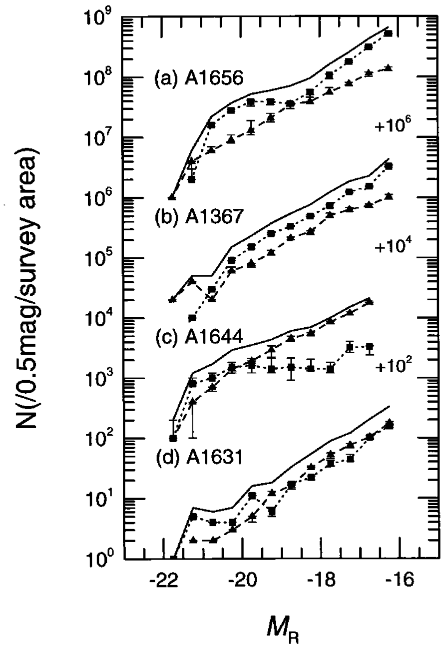


FIG. 2.—Luminosity functions for the total sample and morphological subsamples of each cluster. (*a*) A1656 (curves and symbols are shifted along the ordinate by $\Delta N = 10^6$); (*b*) A1367 ($\Delta N = 10^4$); (*c*) A1644 ($\Delta N = 10^2$); (*d*) A1631. The solid line, the dotted line (plus filled squares), and the dashed line (plus filled triangles) represent the LF of the total sample, the early-type sample, and the late-type sample, respectively. The error bars show the fluctuations when the classification parameter is changed (see text).

part of the LF of all of the cluster is fitted to the Schechter function reasonably well with $P(\chi^2|\nu) = 0.23$–$0.97$. However, the LF in the whole range cannot be fitted to the Schechter function except in the case of A1644. The total LF appears to steepen at $M_R \geq -18$, except for A1644. A hint of a large excess of faint galaxies has been found recently both in clusters (TG; De Propris et al. 1995; Bernstein et al. 1995) and in the fields (Marzke, Huchra, & Geller 1994).

Figure 2 shows the LFs of the total sample (*solid line*), the early-type sample (*dotted line plus filled squares*), and the late-type sample (*dashed line plus filled triangles*) for each cluster. No field correction is applied because the fraction of morphological types is never known with sufficient accuracy to apply corrections to type-specific LFs. The error bars on the counts of the early-type and late-type samples denote the

TABLE 2

BEST-FIT TWO PARAMETERS WITH $\alpha$ FIXED AT $-1.25$

| Cluster | $N^*$ | $M^*$ | $P(\chi^2|\nu)$ |
|---|---|---|---|
| A1656: | | | |
| Whole ........ | 88.38 | −20.20 | 0.00 |
| Bright ........ | 42.82 | −21.14 | 0.31 |
| A1367: | | | |
| Whole ........ | 60.84 | −19.83 | 0.00 |
| Bright ........ | 37.20 | −20.35 | 0.82 |
| A1644: | | | |
| Whole ........ | 27.21 | −21.50 | 0.99 |
| Bright ........ | 26.61 | −21.54 | 0.97 |
| A1631: | | | |
| Whole ........ | 26.47 | −20.12 | 0.00 |
| Bright ........ | 14.55 | −20.77 | 0.23 |

fluctuations when we change the classification parameter $p$ by $\pm 0.05$. Figure 2 reveals an interesting feature that the LFs of late-type galaxies (*dashed lines*) look very similar among the four clusters, while there is variation in the shape of the LFs of early-type galaxies (*dotted lines*). In A1656 the LF of early-type galaxies dominates that of late-type galaxies all over the magnitude range. It also shows a "bump" at $M_R = -20$, which was already reported by Lugger (1986) and TG. An early-type LF of the Virgo Cluster is known to show a similar bump (SBT), and TG discussed the bump in terms of a lognormal shape of the bright portion of the LF. In contrast to the above behavior in A1656, the LF of early-type galaxies in A1644 exceeds the LF of late-type galaxies only in the bright end ($M_R \leq -20$) and levels off in $-20 \leq M_R \leq -18$ with a hint of a slight increase toward the fainter magnitudes. The faint end ($M_R > -18$) of the LF of the total sample of A1644 is dominated by late-type galaxies. The behavior of the LFs of early-type galaxies in A1367 and A1631 is similar to that of late-type galaxies showing the almost linear increase toward faint magnitudes.

The previous studies (e.g., Lugger 1986; Colless 1989) showed that the LF of rich clusters is more or less universal and does not depend on cluster morphology or richness. We find, however, that the apparent universality of the cluster total LF is valid only in the bright part ($M_R \leq -18$). Three clusters whose LFs cannot be fitted well to the Schechter function with $\alpha = -1.25$ all have a large population of faint early-type galaxies ($M_R \leq -18$). A large number of faint galaxies, called dwarf ellipticals (dE's), were found in the Virgo Cluster by SBT. For A1656, the composite LF of E + S0 + dE + dSph derived by TG resembles our early-type LF. TG attributed the abrupt rise of the LF at the faint end

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mostly to dE's. Their dE's, however, may include dE's, dS0's, and possibly the faint end of a normal elliptical population found in Virgo. Detailed classification is difficult at the Coma distance, where images of dwarf galaxies are easily affected by seeing. Virgo dE's are known to show exponential profiles (e.g., Ichikawa, Wakamatsu, & Okamura 1986), and they should be classified as late types according to our method unless the seeing effects are dominant. A comparative study of luminosity profiles of Virgo and Coma dwarf populations using high-resolution images would be extremely important to clarify the apparent mystery.

Finally, we demonstrate that the above behavior of the LFs is not affected by the selection effects of surface brightness or size. First of all, the limiting magnitude of our sample is about 2.5 mag above the detection limit, since it is imposed by the star/galaxy discrimination. In fact, all the sample galaxies were detected even when we took the 3 $\sigma$ threshold instead of 1.5 $\sigma$. We show in Figure 3 the mean surface brightness within the isophote of $\mu_{\rm th}$, the threshold surface brightness, versus the absolute magnitude for A1656 galaxies with the three limits: the limiting magnitude $M_R^{\rm lim}$, the limiting size $N_{\rm pix}^{\rm lim}$, and $\mu_{\rm th}$ ($=1.5$ $\sigma$). Dots are sample galaxies of A1656. There is no sign of selection effects by $\mu_{\rm th}$ or by $N_{\rm pix}^{\rm lim}$. For comparison, we also show in Figure 3 the 83 dE's (*open circles*) in the Virgo Cluster based on the $B$-band data given in Ichikawa (1987). His threshold, 26 mag arcsec$^{-2}$ in $B$, is almost equal to ours, 24.23 mag arcsec$^{-2}$ in $R$. The data are translated on the assumption that $(m - M)_{\rm Virgo} = 31.2$ and $(B - R) = 1.75$, which is the typical color for dwarf galaxies in A1656 (TG). The uncertainties associated with this color estimate are shown by error bars. Our sample includes only the bright part of the Virgo dE population if it is located at the distance of A1656. However, above our limiting magnitude, no such bright dE's are missing in our sample because of low surface brightness or small size.

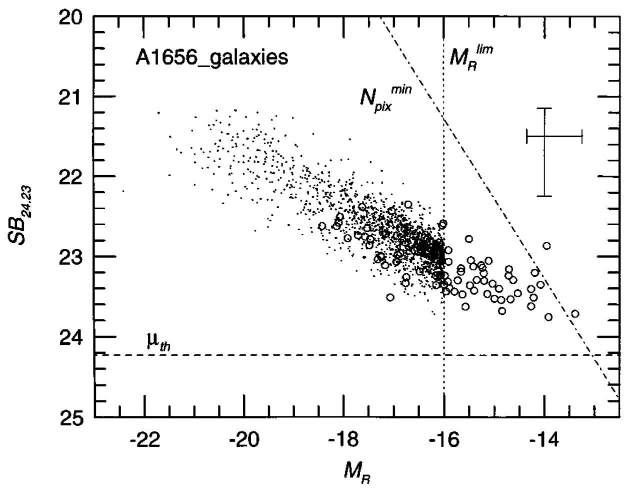


FIG. 3.—Mean surface brightness vs. absolute magnitude diagram with the three limits imposed on our A1656 sample (see text). Dots are A1656 galaxies. Open circles represent the dE's in the Virgo Cluster. The Virgo data are taken from Ichikawa (1987) and translated from the $B$ band to the $R$ band and with $(m - M)_{\rm Virgo} = 31.2$. Uncertainties of this color estimate are shown by error bars.

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## REFERENCES

Bernstein, G. M., Nichol, R. C., Tyson, J. A., Ulmer, M. P., & Wittman, D. 1995, AJ, submitted
Binggeli, B., Sandage, A., & Tammann, G. A. 1988, ARA&A, 26, 509
Burstein, D., & Heiles, C. 1984, ApJ, 54, 33
Colless, M. 1989, MNRAS, 237, 799
De Propris, R., Pritchet, C. J., Harris, W. E., & McClure, R. D. 1995, ApJ, submitted
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., Jr., Buta, R. J., Paturel, G., & Fouqué, P. 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer) (RC3)
Doi, M., Fukugita, M., & Okamura, S. 1993, MNRAS, 264, 832
Dressler, A. 1980, ApJS, 42, 565
Dressler, A., & Shectman, S. A. 1988, AJ, 95, 985
Efstathiou, G., Ellis, R. S., & Peterson, B. A. 1988, MNRAS, 232, 431
Ferguson, H. C., & Sandage, A. 1988, AJ, 96, 1520
Ichikawa, S. 1987, Ann. Tokyo. Astron. Obs., 2d Ser., 21, 437
Ichikawa, S., Wakamatsu, K., & Okamura, S. 1986, ApJS, 60, 475
Kashikawa, N., Sekiguchi, M., Yagi, M., Yasuda, N., Okamura, S., Shimasaku, K., & Doi, M. 1995, in IAU Symp. 167, New Developments in Array Technology and Applications, in press
Kirshner, R. P., Oemler, A., Jr., Schechter, P. L., & Shectman, S. A. 1987, ApJ, 314, 493
Lugger, P. M. 1986, ApJ, 303, 535
Marzke, R. O., Huchra, J. P., & Geller, M. J. 1994, ApJ, 428, 43
Peterson, B. A., Ellis, R. S., Efstathiou, G., Shanks, T., Bean, A. J., Fong, R., & Zen-Long, Z. 1986, MNRAS, 221, 233
Sandage, A., Binggeli, B., & Tammann, G. A. 1985, AJ, 90, 1759 (SBT)
Schechter, P. L. 1976, ApJ, 203, 297
Sekiguchi, M., Iwashita, H., Doi, M., Kashikawa, N., & Okamura, S. 1992, PASP, 104, 744
Thompson, L. A., & Gregory, S. A. 1993, AJ, 106, 2197 (TG)
Yamagata, T., & Yoshii, Y. 1992, AJ, 103, 117
Zabludoff, A. I., Geller, M. J., & Huchra, J. P. 1993, AJ, 106, 1273

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