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MORPHOLOGY CLASSIFICATION OF GALAXIES IN CL 0939+4713 USING A GROUND-BASED TELESCOPE IMAGE

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ABSTRACT

Morphological classification is studied for galaxies in cluster CL 0939+4713 at $z = 0.407$ using simple photometric parameters obtained from a ground-based telescope image with seeing of 1".2 FWHM. By plotting the galaxies in a plane of the concentration parameter versus mean surface brightness, we find a good correlation between the location on the plane and galaxy colors, which are known to correlate with morphological types from a recent *Hubble Space Telescope* study. Using the present method, we expect a success rate of classification into early and late types of about 70% or possibly more.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (CL 0939+4713)— galaxies: fundamental parameters

1. INTRODUCTION

Morphology of distant galaxies provides us with an important clue to understanding galaxy evolution. Butcher & Oemler (1978, 1984) found that galaxies in the rich cluster environment evolve rapidly; the clusters CL 0024+1654 and 3C 295 contain many more blue galaxies that show colors of spiral galaxies than nearby rich clusters do. An extensive study of galaxies in distant clusters was subsequently made by Dressler & Gunn (1992, hereafter DG), which confirmed the Butcher-Oemler effect for a number of distant clusters. A more recent observation using the *Hubble Space Telescope* (*HST*) showed that these blue galaxies are indeed mostly spiral galaxies (Dressler 1993; Dressler et al. 1994). This casts a question as to where these spiral galaxies have gone. This is the best example showing the importance of morphological classification for distant galaxies. Morphological studies are conventionally done with eye inspections, and for distant galaxies they can be made only with the very sharp images of observations from space. Except for the initial attempt with *HST*, available morphology catalogs are hence limited to nearby galaxies at the approximate distance of the Coma or Hercules clusters.

Recently Doi, Fukugita, & Okamura (1993, hereafter DFO) studied morphological classification in a quantified manner using a few simple photometric parameters, which are insensitive to the distance and do not much depend on the seeing and inclinations. They showed that classification, which is in reasonable agreement with the Hubble types, can be made even for rather poor images; using images on Schmidt plates close to the seeing limit for surface photometry, it was demonstrated that morphology of galaxies in the Coma Cluster can be classified, with a frequency of coincidence with RC 3 morphology of 85%–90%, by plotting them on the two-dimensional plane of the concentration index versus surface brightness. This result tempts us to examine whether this simple method works for distant galaxies when image quality is reasonably good. Abraham et al. (1994), in fact, used a method, which is basically identical to that of DFO, and showed that it can be applied successfully to galaxies in A957 at $z = 0.044$ and also made simulations for distant galaxies. In this paper we apply the method of DFO to more distant galaxies in the Dressler-Gunn cluster CL 0939+4713 at $z = 0.407$.

We note that two of the main characteristics of this method, distance independence and seeing insensitivity, are lost at such a great distance. We demonstrate, however, that the method works reasonably well after the effect of the distance and seeing are properly taken into account.

2. FORMULATION

The two parameters which are shown to be useful in DFO are the concentration parameter c_{in} and the mean surface brightness SB. Using the equivalent radius $r(\mu)$ of isophotal image, which is defined by

$$n(\mu)\Delta S = \pi r(\mu)^2 , \qquad (1)$$

with $n(\mu)$ the number of pixels that have a flux that exceeds the surface brightness μ and ΔS the pixel area, the concentration parameter is defined by

$$c_{in}(\alpha) = \frac{\int_0^{\alpha r(\mu_L)} rI(r)dr}{\int_0^{r(\mu_L)} rI(r)dr} , \qquad (2)$$

where $2\pi rI(r)dr$ is the differential flux between r and $r + dr$ with $I(r)$ the flux in a equivalent profile. The value of α is chosen to be 0.3, and μ_L is set at the detection threshold.

When the relativistic effects and the K-correction are negligible, and when the size of galaxy is much larger than the seeing size, the above two parameters are independent of the distance and seeing. For $z \sim 0.4$, however, none of these conditions are satisfied. We calculate the position of the fiducial curves on the c_{in}-SB plane expected for the de Vaucouleurs profile and for the exponential law by carrying out a convolution integral with the point spread function. We take $z = 0.4$, $\mu_L = 26.25$ mag (arcsec)$^{-2}$ for the r band, and the Gaussian point-spread function with FWHM of 1".2, to fit our observational condition (see § 3 below). The K-correction $K(z)$ is also applied using the spectroscopic energy distribution of Coleman, Wu, & Weedman (1980). The relativistic formulation is used in this calculation. Figure 1 shows the prediction for the two profiles for model galaxies with $r = 20.0$–22.0. The separation becomes gradually worse as the magnitude becomes fainter; beyond $r = 21.5$ mag, the two types of galaxies are practically not

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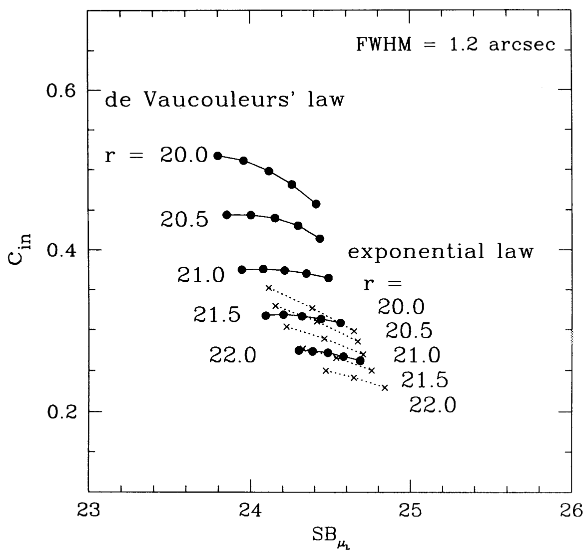


FIG. 1.—Positions on the c_{in}-SB plane expected for galaxies at $z = 0.4$ with the de Vaucouleurs profile (*solid curve*) and for those with the exponential profile (*dotted curve*). We take the FWHM of the point spread function to be 1″2 and $\mu_L = 26.25$ mag (arcsec)$^{-2}$. Five curves correspond to galaxies with different apparent magnitudes, and marks on the curve show galaxies which have $\mu_e(V) = 20$–22.5 mag (0.5 mag step from left to right) in the V band at $z = 0$ for the de Vaucouleurs profile, and 20–21 mag for the exponential profile.

separated, when scatter is taken into account. The magnitude actually represents the size of galaxies, and the position of the curve is primarily determined by the ratio of the size of a galaxy (described by the effective radius r_e of the de Vaucouleurs profile and the scale length of the exponential profile h) to the seeing size. The K-correction and the $(1 + z)^4$ effect for surface brightness make μ_e fainter by 2.0 mag arcsec^{-2} (for bulges) and 1.5 mag arcsec^{-2} (for disks). The predicted position for purely bulge and disk components then moves along the curve.

If we draw a curve in the middle of the two fiducial curves for nearby galaxies (see DFO), 92% of early types (E–S0/a) are located above this division curve and 79% of late types (Sa or later) are below the curve. On the other hand, 29% of galaxies located above the curve are contaminants from later types (mostly Sa–Sab), and 5% of galaxies below the curve are early types (mostly S0–S0a). This division curve roughly corresponds to the $I_{deV}/(I_e + I_{deV}) \sim 0.2$ (which corresponds to the ratio of the flux 0.5) with an assumed scale length $r_e \simeq h$. We also calculate the division line for galaxies at $z = 0.4$ using these parameters. (We note that we applied the K-correction of early-type galaxies to the bulge component for this "spiral" galaxy.) With the use of this line we may expect the performance for morphology classification similar to that for nearby galaxies, if kinematics of galaxies do not change from $z = 0.4$ to 0.

3. DATA

We analyze the CCD picture in the Gunn r band taken with the 4-Shooter camera on the 200 inch (5 m) Palomer Hale Telescope (DG). The covered region is 5′5 × 5′5 which corresponds to $(1.5\ h^{-1}\ \mathrm{Mpc})^2$ in physical units. The details of the observation are given in DG. The most important characteristics for us are that the pixel size is 0″34, and the seeing is ∼1″ FWHM. We use the automated surface photometry software AIMS (Doi, Fukugita, & Okamura 1994) with the lowest isophotal level of the measurement to be 2.5 σ, where σ is the sky background noise per pixel. This detection level corresponds approximately to 26.25 mag (arcsec)$^{-2}$. Whereas we detected all 272 galaxies cataloged in DG, we measured only 210 galaxies among them. The rest of the galaxies are discarded in our analysis, since they are either close to the edges of the field of view, for which flat-fielding is poorly made, or overlapped heavily with other objects so that deblended images are not quite suitable to determine photometric parameters. The magnitudes from our surface photometry (isophotal magnitudes) are checked with those given in DG. The offset between the two magnitudes are those expected from the difference in the definition of the two magnitudes. We obtained a FWHM of 1″2 for the point spread function from stellar images. We adopt this value in the present analysis.

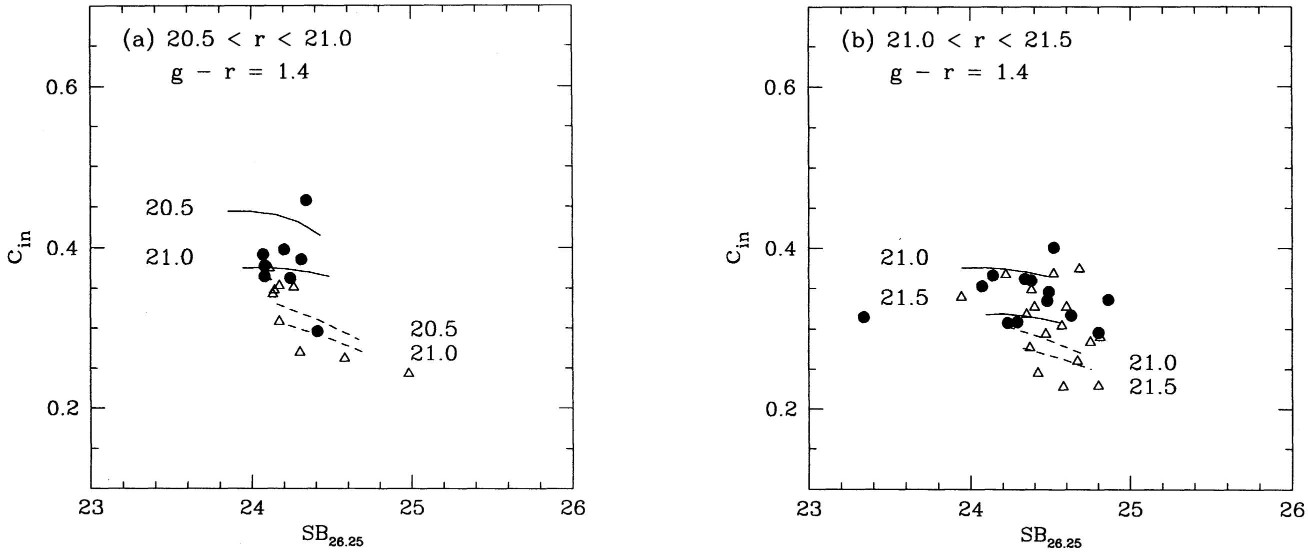
4. RESULTS

The resulting plot on the c_{in}-SB plane is shown in Figure 2 for three magnitude bins: $r = 20.5$–21.0, 21.0–21.5, and 21.5–22.0. The typical errors for c_{in} and SB arising from photon statistics are estimated to be less than 5% for galaxies brighter than $r \sim 22$ mag. The L^* magnitude of the galaxy luminosity function for CL 0939+4713 is expected from typical L^* for nearby clusters to be about $r = 20.1 + 5 \log h$ mag ($\Omega = 0.1$ assumed). We do not use galaxies brighter than $r = 21.0$, since they may be rather strongly contaminated by foreground galaxies, as indicated by sample spectroscopic data of DG. Since the catalog of the *HST* survey is not published yet, we classify galaxies into two types according to their colors; solid circles are galaxies with $g - r > 1.4$, and open circles denote galaxies with $g - r < 1.4$. The preliminary result of the *HST* observation (Dressler 1993; Dressler et al. 1993) indicates that the colors of elliptical galaxies of CL 0939+4713 show small scatter, and they are within $g - r = 1.6 \pm 0.2$: more quantitatively, 75% of galaxies with $g - r > 1.4$ are early type (E–S0) galaxies, whereas galaxies with $g - r < 1.4$ are mostly (75%) spirals. Therefore, we consider that these two classes of galaxies represent galaxy types reasonably well.

We also plot in the same figure two curves for the de Vaucouleurs profile and the exponential disk, as calculated in § 2. We find that the offset between r_r used in DG's catalog and the r magnitude is 0.2 mag. We carry out morphology classification using $r_r = r + 0.2$ mag.

We see an obvious correlation between the color and the position on the c_{in}-SB plane for the two brighter samples shown in Figures 2*a* and 2*b*. If we draw a line in the middle of the two fiducial curves, all redder galaxies are included in the upper part of the line. On the other hand, blue galaxies show more scatter, though they are distributed relatively in a lower part. This is qualitatively similar to what we have seen for nearby galaxies (DFO).

By classifying the galaxies into early and late types using the division line, which corresponds to the curve in the middle of the two curves for nearby galaxies, we find that 72% of redder galaxies are located above the line and 70% of bluer galaxies are below the line. (Table 1 shows classification of morphological types for galaxies between $r + 0.2 = 20.5$ mag and 22.0 mag.) This demonstrates the power of the morphological classification of the present method. The percentage is somewhat worse than expected from nearby sample (§ 2). We note, however, that the color information does not represent accu-



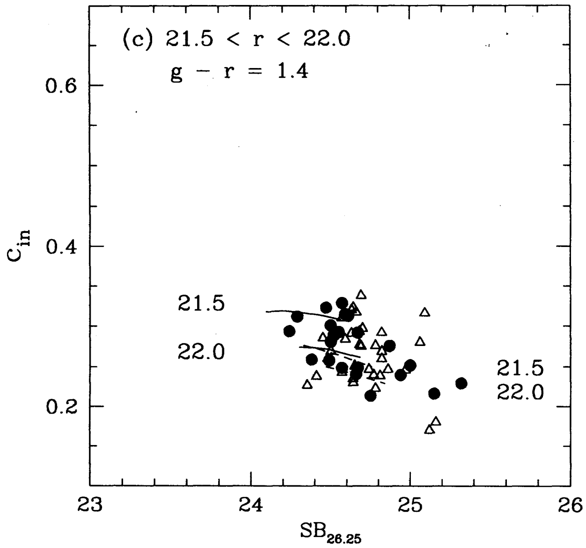


FIG. 2.—Plot of galaxies of CL 0939+4713 on the c_{in}-SB plane. The three figures are for (*a*) $r = 20.5$–21.0 mag, (*b*) $r = 21$–21.5 mag, and (*c*) $r = 21.5$–22 mag. Solid circles are galaxies with $g - r > 1.4$ and triangles are those with $g - r < 1.4$. The curves are those expected for galaxies with the de Vaucouleurs profile (*solid curve*) and the exponential profile (*dotted curve*) for the relevant magnitude range.

TABLE 1

MORPHOLOGY CLASSIFICATION OF GALAXIES

$r + 0.2$ (mag)	Type	Early	Late	Sum
20.5–21.0......	Red	9	2	11
	Blue	3	10	13
	Sum	12	12	24
21.0–21.5......	Red	7	4	11
	Blue	5	5	10
	Sum	12	9	21
21.5–22.0......	Red	10	4	14
	Blue	8	23	31
	Sum	18	27	45
Total	Red	26	10	36
	Blue	16	38	54
	Sum	42	48	90

rate morphology of galaxies. A better estimate of the power of this classification technique can be made after the morphology using *HST* images become available. We also note that contamination of fore/background galaxies and stars are expected at 20% level. It may also be a cause of a larger scatter that clusters have more S0–Sa galaxies than in the field; these intermediate Hubble types are not clearly classified with the present method.

For the fainter sample (Fig. 2*c*) with $r = 21.5$–22.0, we do not see any separation into two classes, but this is what we expect from our calculation.

5. SUMMARY AND DISCUSSION

We have shown that the method of morphology classification proposed in DFO applies well to high-redshift galaxies at $z = 0.4$, if a careful treatment is made for the predicted positions, by taking account of the seeing effect and redshift of galaxies. The analysis shown in this present work, using the method of DFO, indicates morphology classification into the

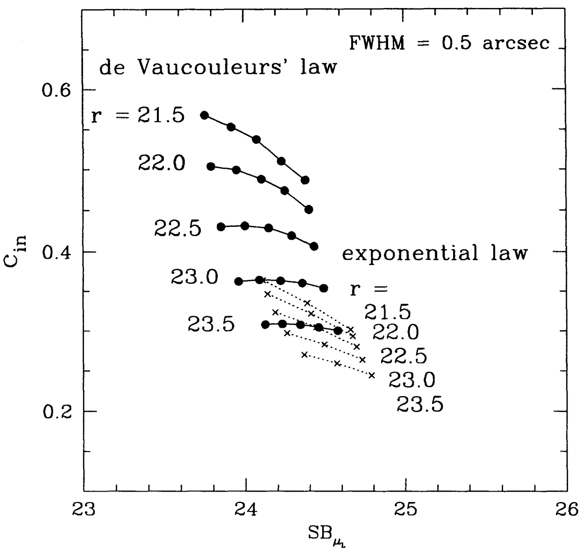


FIG. 3.—As Fig. 1, but the FWHM of the seeing is assumed to be 0″.5

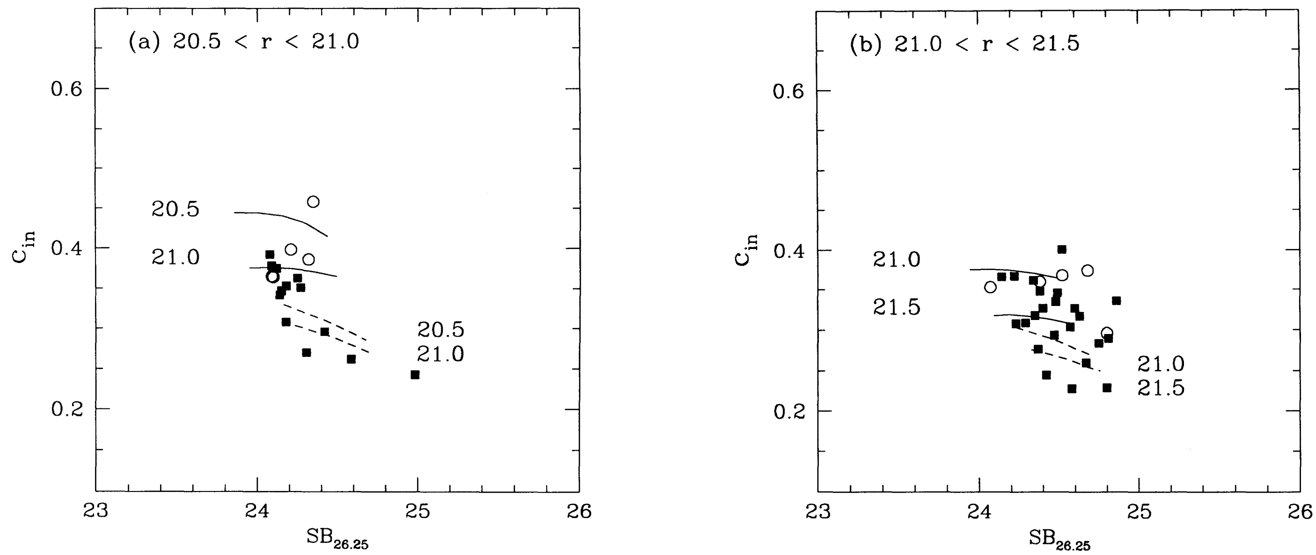


FIG. 4.—As Fig. 2, but solid squares denote *e*-type galaxies, and open circles denote *d*-type galaxies classified by Dressler & Gunn. (*a*) $r = 20.5$–21.0 mag and (*b*) $r = 21$–21.5 mag.

conventional Hubble type at a 70% confidence level, or possibly more. When the morphology catalog becomes available from *HST* studies, the confidence level will be more securely estimated. On the other hand, the present analysis shows that the redshift information is indispensable, unlike the case for nearby ($z < 0.05$–0.1) galaxies, to make the classification, and that a rather accurate knowledge is necessary for the image size.

We note that the image of DG is rather close to the seeing limit for surface photometry, just as DFO encountered with their data for the Coma Cluster. If seeing is better, FWHM of 0".5, say, the power of classification increases drastically. In Figure 3 we plot a figure similar to Figure 1 but for the case of 0".5 seeing. The figure shows that the curves for the de Vaucouleurs profile move upward by 1.7 mag, whereas those for exponential disk are little affected. This raises the limiting magnitude for morphology classification to 23.2r mag, 2 mag below L^* (cluster). We also estimate that this classification method remains reliable to $z \sim 0.7$–0.8 for an L^* galaxy.

One may compare the morphology classification in the present method with that presented in DG, which is based on the relative quality of explicit fittings of the exponential or the de Vaucouleurs form to the image profile, using a large number of two-dimensional templets. Figure 4 shows the correlation of the latter classification with ours for $r = 21$–21.5 mag and 21.5–22 mag samples: indeed, galaxies classified as *d* type (fit better with de Vaucouleurs profile) are located close to the upper envelope of the c_{in}-SB plot, although a greater number of galaxies are classified as *e* type (fit better with exponential) in the DG classification. We remark that the 32% of redder galaxies ($r - g > 1.4$) are classified as the *d* type and 82% of bluer galaxies are given *e* types by DG (a large percentage for *e* type is the manifestation of the fact that predominant numbers [$\sim$80%] of galaxies are given *e* type in this magnitude range). This means that our c_{in}-SB method yields better correlation with the colors.

It is interesting to see the difference in the performance of the two methods, direct profile fitting and the c_{in}-SB method as we discussed here. The two methods are basically based on the same principle using the galaxy profile, yet their performances are somewhat different. The explicit fitting uses full information of the profile. On the other hand, the method by DFO uses integral information from the luminosity profiles, which, however, are chosen so that they are not sensitive to inclination.

Our final remark is that the present method, which uses only the output that surface photometry routinely produces, would be useful for morphology classification in full automated digitized sky surveys expected in the near future.

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Note added in manuscript (1994 September 15). Dressler et al. (1994) have now published a catalog of galaxies in CL 0939+4713, in which morphological classification is given in a traditional way from a study of *HST* observations. By comparing our catalog with that of Dressler et al., it is found that the coincidence frequency of the classification of the present paper with that given in Dressler et al. is about 70%.

REFERENCES

Abraham, R. G., Valdes, F., Yee, H. K. C., & van den Bergh, S. 1994, ApJ, 432, 75
Butcher, H., & Oemler, A. 1978, ApJ, 219, 18
———. 1984, ApJ, 285, 426
Coleman, G. D., Wu, C., & Weedman, D. W. 1980, ApJS, 43, 393
Doi, M., Fukugita, M., & Okamura, S. 1993, MNRAS, 264, 832 (DFO)
Doi, M., Fukugita, M., & Okamura, S. 1994, ApJS, in press
Dressler, A. 1993, in Observational Cosmology, ed. G. Chincarini, A. Iovino, T. Maccacaro, & D. Maccagni (ASP Conf. Ser., 51), 225
Dressler, A., & Gunn, J. E. 1992, ApJS, 78, 1 (DG)
Dressler, A., Oemler, A., Butcher, H., & Gunn, J. E. 1994, ApJ, 430, 107