THE ASTROPHYSICAL JOURNAL, **274**:L49–L52, 1983 November 15

DIAMETER VERSUS SURFACE BRIGHTNESS DIAGRAM OF GALAXIES

K. KODAIRA, S. OKAMURA, AND M. WATANABE
Tokyo Astronomical Observatory, University of Tokyo
Received 1983 June 27; accepted 1983 July 20

ABSTRACT

The diameter versus surface brightness diagram is presented for 149 galaxies in the Virgo and the Ursa Major Clusters based upon a homogeneous data set of digital surface photometry. From the principal component analysis of photometric parameters, these two coordinates of the diagram are found to be most relevant to the study of the characteristics of galaxies. Two distinct branches are recognized for the distribution of galaxies in the diagram, and their meanings are discussed. The potential important uses of the diagram are pointed out, as the basis of a quantitative classification of galaxies and a characterization of clusters of galaxies.

Subject headings: galaxies: clustering — galaxies: structure

I. INTRODUCTION

In a series of studies toward a quantitative classification of galaxies (Watanabe, Kodaira, and Okamura 1982, Paper I; Watanabe 1983, hereafter Paper II; Okamura, Kodaira, and Watanabe, hereafter Paper III), we carried out digital surface photometry for a sample of 261 galaxies in the Virgo and the Ursa Major regions. Basic photometric data are given in Papers II and III. This *Letter* presents the diameter versus surface brightness diagram (DSBD) based upon these data and discusses its potential importance to the study of galaxies.

Most of the sample galaxies are members of either the Virgo or the Ursa Major Clusters. Their distance moduli from the latest version of the infrared magnitude/H I velocity width relation are 31.08 ± 0.11 and 31.15 ± 0.08 respectively (Aaronson and Mould 1983). The two clusters are thus at nearly equal distance, and this greatly reduces the uncertainties inherent to the extragalactic work. Exact distances to these clusters, however, still remain controversial (e.g., Aaronson and Mould 1983; de Vaucouleurs 1982). A distance of 16.6 Mpc, $(m - M)_0 = 31.1$, is assumed in this *Letter* for both the Virgo and the Ursa Major Clusters.

II. PRINCIPAL COMPONENT ANALYSIS

Following the pioneering work by Brosche (1973), we apply principal component analysis to a set of photometric parameters of the 261 galaxies. Details of the analysis will be given elsewhere (Watanabe, Okamura, and Kodaira 1983). The parameters involved are the integrated magnitude (V_{26}), the diameter ($\log D_{26}$), the mean surface brightness (SB) within D_{26}, and an index $XI(P)$, which is a measure of luminosity concentration analogous to C_{21} and C_{32} introduced by de Vaucouleurs (1977*a*, *b*). These parameters were defined and derived in Papers II and III using the generalized radial profile (see Paper I) in the V band within a limiting surface brightness of 26 mag arcsec^{-2}.

The main results of the analysis are the following. (1) There are only two significant independent variables, i.e., principal components, Y_1 and Y_2, which carry 64% and 29% of the total variance. (2) Our principal components closely coincide with those derived by Brosche (1973). This indicates that the global structure of galaxies may be characterized by photometric parameters alone without dynamical parameters. (3) Gradients of $\log D_{26}$ and SB projected onto the (Y_1, Y_2) plane are nearly orthogonal (92°). These results suggest that the (SB, $\log D_{26}$)-diagram would be a highly efficient tool to study the global structure of galaxies. The $XI(P)$ versus SB diagram presented in Paper III may complement this diagram.

III. DIAMETER VERSUS SURFACE BRIGHTNESS DIAGRAM

We construct the DSBD for the sample galaxies. Diameter and surface brightness are expressed in units of 0.′1 and mag arcsec^{-2} respectively. In order to minimize the admixture of noncluster members, we limit the present sample to the galaxies with a known radial velocity of $V_0 < 3500$ km s^{-1}. Out of the 261 galaxies, 201 were left after a survey of the literature (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC2; Eastmond and Abell 1978; Sandage and Tammann 1981; Karachentsev and Karachentseva 1982; Bottinelli, Gouguenheim, and Paturel 1982; Aaronson *et al.* 1982).

Figure 1 shows the DSBD for 149 galaxies which are selected from the 201 galaxies according to the following criteria: (1) galaxies of types earlier than S0/a (morpho-

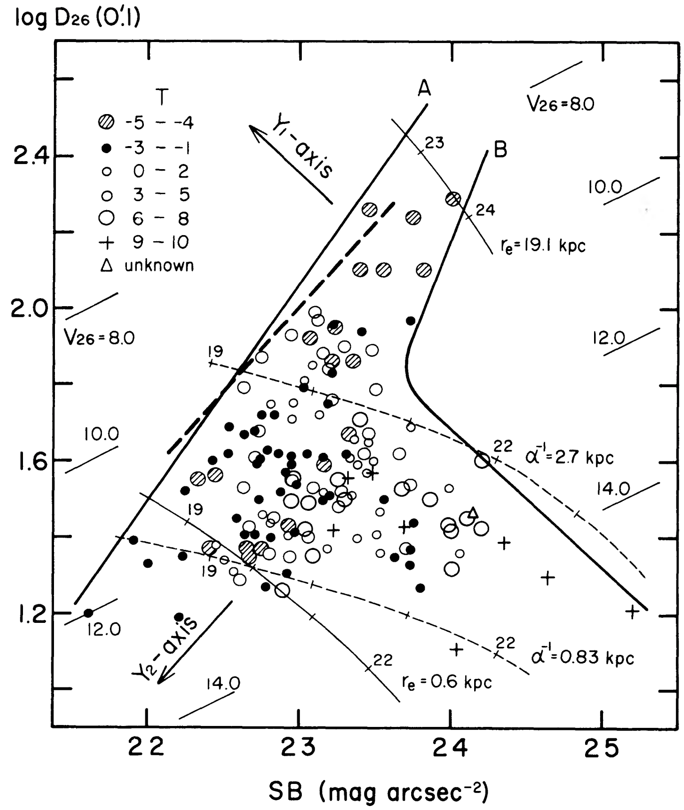

FIG. 1.—The diameter vs. surface brightness diagram for 149 galaxies in the Virgo and the Ursa Major Clusters. Projections of the axes of the two significant principal components and the lines of constant magnitude are shown. The thick solid curves (A and B) show the boundaries of the observed distribution. The thin solid and broken curves represent some homologous families for the $r^{1/4}$-law and exponential law respectively (see text). The tick marks on the curves indicate an interval of 1 mag in the brightness-scale parameter, numerals on the tick marks indicating the parameter value in units of mag arcsec^{-2}. The thick broken line corresponds to the relation between μ_e and r_e found by Kormendy (1980).

logical type index in RC2 $T < 0$); (2) the apparent axial ratio b/a is larger than 0.4 for galaxies with $T > 0$ or with an uncertain or unknown T. The values of b/a are taken from Paper II. The second criterion is adopted to exclude the galaxies whose photometric data might be substantially affected by internal absorption. The only exception is NGC 3718, which shows unusual absorption features (see Sandage 1961) and is not included in Figure 1.

In the DSBD shown in Figure 1, we note the following. (1) There are two well-defined boundaries (*solid curves*) which limit the distribution of galaxies at the left (*line A*) and right (*curve B*) sides in addition to the spurious boundary at log $D_{26} \sim 1.3$ due to the selection effect (see Paper II). (2) With the boundaries, the distribution forms two distinct branches that run almost parallel to the projected Y_1 and Y_2 axes respectively. (3) The branch along the projected Y_2 axis is formed mainly by elliptical and S0 galaxies, while that along the projected Y_1 axis consists of spiral galaxies, especially late-type spiral and irregular galaxies.

The same plot as Figure 1 but for 51 highly inclined galaxies with $b/a < 0.4$ shows a systematic shift of the distribution toward fainter surface brightness. An *average* internal absorption is inferred to be $\Delta m \sim 0.4$ mag from the shift.

IV. DISCUSSION

The radial luminosity profile of galaxies can be modeled with two parameters, i.e., the brightness-scale parameter and the length-scale parameter. On the basis of the conventional formulae,

$$I(r) = I_0 \exp(-\alpha r), \quad (1)$$

for exponential disks and

$$\log I(r)/I_e = -3.33 \left[(r/r_e)^{1/4} - 1 \right], \quad (2)$$

for the $r^{1/4}$-law elliptical galaxies (Freeman 1970; de

Vaucouleurs 1948, 1977*a*), we can compute log D_{26} and SB to compare model sequences with observations in the DSBD.

We consider a family of galaxies whose luminosity profiles have (1) the same shape, i.e., either exponential or $r^{1/4}$-law, (2) the same length-scale parameter α^{-1} or r_e, and (3) different brightness-scale parameters I_0 or I_e. This family is called the "homologous family." The thin solid and broken curves in Figure 1 show the sequences of galaxies in some homologous families for the $r^{1/4}$-law and exponential law respectively. Galactic extinction of $A_v = 0.16$ mag is assumed (see RC2) throughout the computation in this section. Curves of homologous families of both exponential law and $r^{1/4}$-law run approximately along the projected Y_1 axis, and the direction of increasing brightness-scale parameter roughly coincides with that of increasing Y_1. Thus the branch along the projected Y_1 axis may be named the "homologous branch." The upper boundaries of elliptical and late-type spiral galaxies in the homologous branch correspond to $r_e \sim 19$ kpc and $\alpha^{-1} \sim 3$ kpc, respectively, as shown in Figure 1. The boundary A suggests the existence of an upper limit of the brightness-scale parameter in the form of $I_{0,\max}(\alpha^{-1})$ or $I_{e,\max}(r_e)$. Accordingly, the branch along the projected Y_2 axis may be named the "saturation branch."

Kormendy (1977, 1980) found a tight correlation between μ_e, the brightness-scale parameter I_e in units of mag arcsec^{-2}, and r_e for elliptical and bulge-dominant S0 galaxies on the basis of parameters derived from the profile along a line at 45° to the major axis. The mean relation he found is expressed by

$$\mu_e(B) = 3.28 \log r_e(\text{kpc}) + 19.45, \qquad (3)$$

for $19.8 < \mu_e(B) < 23.3$ mag arcsec^{-2}. A distance of 22 Mpc was assigned to the Virgo galaxies in his sample. With this distance and the assumption of $(B - V) = 0.9$ for elliptical galaxies, equation (3) corresponds to a linear relation in the DSBD

$$\log D_{26} = 0.447\ \text{SB} - 8.274, \qquad (4)$$

for the Virgo Cluster. In computing D_{26} and SB, the $r^{1/4}$-law profile with Kormendy's parameters is substituted for the generalized radial profile. It is noted that equation (4) is independent of the true distance or the distance assumed here. This relation is shown in Figure 1 by the thick broken line for the range of $18.7 < \mu_e(V) < 22.4$ mag arcsec^{-2}. The nearly equal gradient of equation (4) to the saturation branch strongly suggests that the narrow saturation branch represents the same relation that Kormendy (1977, 1980) found.

The members of the saturation branch with log $D_{26} \geq 2.0$ may be distinguished from the smaller members because they are no longer located on the brightest tip of any homologous sequence. The point with log $D_{26} \sim 2.0$ on the saturation branch corresponds to $V_{26} \sim 10.0$, that is, $M_V \sim -21.1$ with the assumed distance. It is remarkable that this value is close to $M_V^* = -21.2$, which is the absolute magnitude corresponding to the discontinuity in the luminosity function of clusters of galaxies and claimed to be universal (e.g., Austin, Godwin, and Peach 1975; Schechter 1976).

The recent compilation of the ratio of the maximum rotational velocity V to the mean velocity dispersion σ of elliptical galaxies by Davies *et al.* (1983) included data for nine galaxies in the present sample. Among six giant elliptical galaxies with log $D_{26} > 2.0$, five have small values of $(V/\sigma)^* < 0.4$, where $(V/\sigma)^*$ is the ratio of the observed value of V/σ to that for a model which has an oblate spheroidal shape of constant ellipticity with isotropic velocity distribution. The only exception is NGC 4636. There is, however, evidence that NGC 4636 is an S0 galaxy (Kormendy 1977). A general tendency that $(V/\sigma)^*$ decreases toward the large-diameter end of the saturation branch is observed. This may be related to the formation history of galaxies on this branch.

When DSBDs are constructed separately for the Virgo galaxies and the Ursa Major galaxies, we notice that there is no significant difference in the distribution domain between the two sets of data except that all the bright elliptical galaxies with log $D_{26} > 2.0$ belong to the Virgo Cluster. The DSBD may thus serve to characterize individual clusters or groups of galaxies. If the upper boundary of the saturation branch (boundary A) is universal, one can estimate the distances of clusters of galaxies relative to the Virgo Cluster by a vertical shift of DSBDs for the coincidence of the distribution domains. When this method is preliminarily applied to the R-band data (Strom and Strom 1978) of the Coma Cluster members with an assumption of $V - R = 0.5$, we find a difference in the distance modulus of $\Delta(m - M)_0 = 3.2 \pm 0.2$ between the two clusters. This value leads to a Hubble constant of 92 ± 8 km s^{-1} Mpc^{-1} with the adopted radial velocity of 6700 km s^{-1} for the Coma Cluster.

In summary, we find the DSBD highly instructive in investigating the global physical properties of galaxies and propose to use the diagram as one of the basic tools to investigate the nature of galaxies and clusters of galaxies.

We thank Dr. B. Takase for his continuous encouragement, Dr. R. D. Cannon for a careful reading of the manuscript, and Mrs. K. Sakurai for drawing the figure and typing the manuscript.

REFERENCES

Aaronson, M., *et al.* 1982, *Ap. J. Suppl.*, **50**, 241.
Aaronson, M., and Mould, J. R. 1983, *Ap. J.*, **265**, 1.
Austin, T. B., Godwin, J. G., and Peach, J. V. 1975, *M.N.R.A.S.*, **171**, 135.
Bottinelli, L., Gouguenheim, L., and Paturel, G. 1982, *Astr. Ap. Suppl.*, **47**, 171.
Brosche, P. 1973, *Astr. Ap.*, **23**, 259.
Davies, R. L., Efstathiou, G., Fall, S. M., Illingworth, G., and Schechter, P. L. 1983, *Ap. J.*, **266**, 41.
de Vaucouleurs, G. 1948, *Ann. d'Ap.*, **11**, 247.
______. 1977*a*, *Ap. J. Suppl.*, **33**, 211.
______. 1977*b*, *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley and R. B. Larson (New Haven: Yale University Observatory), p. 43.
______. 1982, *The Cosmic Distance Scale and the Hubble Constant* (Canberra, Australia: Mount Stromlo and Siding Spring Observatories, Australian National University).
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G., Jr. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press) (RC2).
Eastmond, T. S., and Abell, G. O. 1978, *Pub. A.S.P.*, **90**, 367.
Freeman, K. C. 1970, *Ap. J.*, **160**, 811.
Karachentsev, I. D., and Karachentseva, V. E. 1982, *Soviet Astr. Letters*, **8**, 104.
Kormendy, J. 1977, *Ap. J.*, **218**, 333.
______. 1980, *Proc. ESO Workshop on Two Dimensional Photometry*, ed. P. Crane and K. Kjar, p. 191.
Okamura, S., Kodaira, K., and Watanabe, M. 1983, *Ap. J.*, submitted (Paper III).
Sandage, A. 1961, *The Hubble Atlas of Galaxies* (Washington, D.C.: Carnegie Institution of Washington).
Sandage, A., and Tamman, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington, D.C.: Carnegie Institution of Washington).
Schechter, P. L. 1976, *Ap. J.*, **203**, 297.
Strom, S. E., and Strom, K. M. 1978, *A.J.*, **78**, 73.
Watanabe, M. 1983, *Ann. Tokyo Astr. Obs.*, **19**, 121 (Paper II).
Watanabe, M., Kodaira, K., and Okamura, S. 1982, *Ap. J. Suppl.*, **50**, 1 (Paper I).
Watanabe, M., Okamura, S., and Kodaira, K. 1983, in preparation.

KEIICHI KODAIRA: Tokyo Astronomical Observatory, Mitaka, Tokyo 181, Japan

SADANORI OKAMURA: Kiso Observatory, Tokyo Astronomical Observatory, Mitake-mura, Kiso-gun, Nagano-ken, 397-01, Japan

MASAAKI WATANABE: Tokyo Astronomical Observatory, Mitaka, Tokyo 181, Japan