QUANTITATIVE CLASSIFICATION OF THE GALAXY FROM NEW DATA ON THE PHOTOMETRIC PROPERTIES OF ITS SPHEROIDAL AND DISK COMPONENTS

G. de Vaucouleurs
The University of Texas at Austin

Abstract. After a brief review of previous attempts at identifying the morphological type of our Galaxy by optical or radio methods, a new approach from surface photometry is described. A two-component model consisting of an $R^{\frac{1}{4}}$ spheroid and an exponential disk is fit to the local galactic disk brightness inferred from star counts and to new observations of the brightness distribution in the bulge along the galactic prime meridian. All parameters are in close quantitative agreement with corresponding quantities for Sbc II galaxies and confirm the AB(rs) morphology first proposed in 1963 (IAU Symposium No. 20). An average of NGC 1073, 4303, 5921 and 6744 described in 1969 (IAU Symposium No. 38) closely approximates the photometric properties of our Galaxy.

1. INTRODUCTION

Identification of the morphological type of our Galaxy in the classification system of galaxies (de Vaucouleurs 1959, Sandage 1961, 1975) requires determination of its class (spiral from all evidence), family (ordinary A, transition AB, or barred B), variety (ringed r, mixed rs, or spiral s), and stage (a to m) along the Hubble sequence. The latter characteristic is the most important because it is most closely related to physical parameters such as bulge to disk ratio, hydrogen ratio, mass-luminosity ratio, etc. while the other two seem to be mainly determined by minor, and perhaps transient, dynamical details. In addition, we need to determine the luminosity class, or better, the absolute magnitudes, color indices, scale lengths, and other photometric parameters of the bulge, the disk and the Galaxy as a whole.

Optical observations are best suited to define the stage and scale parameters while radio observations are essential (but perhaps not sufficient) to analyze the spiral structure of the disk which defines the family and variety characteristics. Optical and infra-red observations of the galactic bulge by comparison with M31 have suggested a galaxy type Sb (Baade 1951, Arp 1965) or more precisely Sb to Sb^+, luminosity

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 203–209.

class I-II (Schmidt-Kaler and Schlosser 1973, Maihara et al. 1978). The spiral patterns derived from 21 cm observations or from models of the radio continuum distribution are generally consistent with types Sb or Sc and both have been suggested (Mills 1959, Oort, Kerr and Westerhout 1958, Becker 1964, Kerr and Westerhout 1965, Kerr 1969, 1970, Simonson 1976). However, radio models have either an excessive amount of detail due to confusion between distance and velocity differences or too little due to gross oversimplification of the model. They look unrealistic, in particular the spirals in the 2-arms models make too many turns. Optical studies of the multiplicity of the spiral pattern, by analogy with M101, have suggested a type as late as SAB(rs)cd (Courtès 1972). However, multiplicity of the spiral pattern is correlated with family and variety, not with Hubble stage (de Vaucouleurs 1959, 1963; Sandage 1975). A better approach combining radio and optical data on HII regions has been recently developed by the Georgelins (1976 and references therein). It leads to a more plausible 4-arms spiral pattern and suggests a type closer to Sc than Sb.

The radio and optical evidence for an incomplete ring of giant HII regions in the inner regions of the galaxy, the "3-kpc arm" and the radial outflow of gas in the direction of the galactic center have led to the suggestion that a bar and ring structure are present in the central regions of the galaxy (de Vaucouleurs 1964, Kerr 1967, 1969). Computer models of the HI kinematics in the inner regions of the Galaxy tend to support this view (Simonson and Mader 1973, Peters 1975, Simonson 1976). A statistical evaluation of all available criteria (de Vaucouleurs 1970) has lead to the proposal that SAB(rs)bc is the most probable morphological type of our Galaxy. A good example of this type is NGC 4303. Examples of SAB(r), SB(rs) and SB(r) which are other possible types include NGC 6744, 1073 and 5921 (de Vaucouleurs 1964, 1970). The quantitative comparisons presented below strengthen the similarities.

2. QUANTITATIVE CLASSIFICATION OF GALAXIES

Since I last reviewed the evidence on the morphological type of our Galaxy at the Basel symposium in 1969 a great deal of progress has been made toward a quantitative classification of galaxies (de Vaucouleurs 1977a). In particular the concept of bulge to disk ratio -- one of the two fundamental criteria of the Hubble classification system -- can be precisely defined by the decomposition of the luminosity profile I(r) into two major components, (I) a spheroidal component obeying the $r^{1/4}$ law, and (II) a disk component having an exponential distribution (de Vaucouleurs 1959, 1962, 1974; Freeman 1970; Schweizer 1976). Then $k_I = L^I/L_T$, the fraction of the total luminosity L_T contributed by the spheroidal component and the ratio r_e^I/r_e of its effective radius to that of the whole galaxy are quantitative measures of the bulge to disk ratio.

A number of important physical and kinematical parameters are closely related to the Hubble stage index (T = 1 to 9 from Sa to Sm) and to the luminosity index $\Lambda = (T + L)/10$, where L is the luminosity class (L = 1 to 9 from SI to SV) as reported to the Yale Conference last year (de Vaucouleurs 1977a).

3. A TWO-COMPONENT MODEL OF THE GALAXY

A spheroid + disk model is completely determined by the effective parameters r_e, I_e of each component. The effective radius r_e^I of the galactic spheroid can be estimated from the distribution of globular clusters which obey closely the $r^{1/4}$ law (de Vaucouleurs 1977b) in both the Galaxy and M31, and in the latter with precisely the same scale factor as the luminosity distribution in the spheroid (de Vaucouleurs and Buta 1978). Photometric observations of the galactic bulge along the prime meridian provide a test of the validity of the model and give the brightness scale factor I_e^I. Then the total luminosity of the spheroid is $L_I = 7.268\pi I_e^I(r_e^I)^2$. The effective radius r_e^{II} of the exponential disk can be derived from the surface brightness of the disk near the sun $\mu^{II}(r_o) = 24.16$ mag sec^{-2} calculated from star counts and from the assumption that its apparent face on surface brightness at the center is $\mu_B^{II}(0) = 21.65 \pm 0.3$ mag sec^{-2} (Freeman 1970). The validity of this assumption was verified a posteriori by comparison of the derived standard isophotal diameter D_o (at $\mu_B = 25.0$ mag sec^{-2}) with independent estimates. Then $L_{II} = 3.803\pi I_e^{II}(r_e^{II})^2$ and the total luminosity is $L_T = L_I + L_{II}$.

A model based on these principles was recently constructed in collaboration with W. D. Pence. This model assumes a solar galactocentric distance $r_o = 8.0$ kpc; it is consistent with the face on total surface brightness (disk + spheroid) inferred from star counts $\mu_B(r_o) =$ 23.93 mag sec^{-2} (for an absorbing layer of constant optical depth $A_B = 0.4$ mag) and gives a good representation of new observations of the luminosity distribution along the galactic prime meridian with the 0.9-m reflector at McDonald Observatory. Two cases were considered: (a) a spherical bulge of effective radius $r_e^I = 2.67$ kpc, suggested by the distribution of globular clusters (de Vaucouleurs and Buta 1978), and (b) an ellipsoidal bulge of effective radius $a_e^I = r_e^I/(0.6)^{1/2} =$ 3.45 kpc, if the axis ratio is c/a = 0.6 as suggested by infra-red photometry of the central regions (Maihara et al. 1978). The results differ little, except that the fractional luminosity k_I of the spheroidal component is 28% in case (a) and 40% in case (b). Since the true situation is intermediate between these two extreme cases the averages of the two solutions are adopted in what follows.

4. GALACTIC PARAMETERS

For a distant observer the face-on total magnitude of the Galaxy is $M_T^o(B) = -20.08$; the corresponding luminosity is $L_T(B) = 1.6.10^{10} \mathcal{L}_\odot$ of which half is emitted within the effective radius $r_e = 5.1$ kpc. The fraction $k_I = L^I/L_T = 0.34 \pm 0.04$ contributed by the spheroidal

https://doi.org/10.1017/S0074180900014480 Published online by Cambridge University Press

component is in close agreement with corresponding values for the Sbc (T = 4) galaxies NGC 5194 (k_I = 0.32) and NGC 6744 (k_I = 0.33); it is definitely less than in M31 (Sb, T = 3, k_I = 0.45), but more than in NGC 253 (Sc, T = 5, k_I = 0.15) (de Vaucouleurs 1958, Pence 1978). This is a strong indication that the Hubble stage of our Galaxy is Sbc, or T = 4 ± 0.5.

The calculated face-on isophotal diameter of the Galaxy at the μ_B = 25.0 level is D_o = 23.0 kpc. This is in close agreement with three independent estimates from statistical relations for spiral galaxies: (a) if $V_M = V(R_M)$ is the maximum rotational velocity, a sample of 18 well-observed galaxies shows that $\log V_M + \log(2R_M/D_o) = 2.18 \pm 0.03$ is a constant independent of morphological type and luminosity class (de Vaucouleurs 1977a). In our Galaxy V_M = 255 kms^{-1} and R_M = 7.0 kpc (for r_o = 8.0) imply D_o = 23.4 kpc, (b) if D_1 is the diameter of the largest ring-shaped HII region, a sample of 10 nearby spirals shows that $\log D_o/D_1 = 1.98 - 0.135(M_T^o + 20)$ for all types Sb and later (de Vaucouleurs 1978c). In our Galaxy $D_1 \geq 220$ pc (the Gum nebula) and M_T^o = -20.1 imply $D_o \geq 21.5$ kpc, (c) both V_M and D_o are statistically related to the luminosity index Λ by $\log V_M = 2.15 - (\Lambda - 1)$ and $\log D_o = 4.18 - 0.6(\Lambda - 1)$ (de Vaucouleurs 1977a, 1978a). For V_M = 255 kms^{-1} these two relations imply D_o = 21.6 kpc.

The three independent estimates of D_o are in good agreement with each other and with the value derived from the two-component model. This proves that the mean luminosity gradient of the disk between 8 and 11.5 kpc is very nearly the same as between 0 and 8 kpc. Conversely this can be taken as evidence that the "Freeman constant" $\mu^I(0)$ = 21.65 applies to our Galaxy.

The luminosity index of the Galaxy derived from the two equations above are $\Lambda(V_M)$ = 0.75 and $\Lambda(D_o)$ = 0.70; a third estimate from the correlation between Λ and absolute magnitude (de Vaucouleurs 1978d) $M_T^o = -19.15 + 3.0(\Lambda - 1)$ gives $\Lambda(M_T^o)$ = 0.69, if M_T^o = -20.08. The three determinations are in remarkably close agreement with $\langle\Lambda\rangle$ = 0.71 ± 0.03. Since the most probable combination of morphological type T and luminosity class L is T = L + 1, with a dispersion σ = 1.4 (de Vaucouleurs 1977a, 1978d), the previous conclusion that T = 4 ± 0.5 implies that L = 3 ± 1. In conventional notation this means a classification Sbc II.

The mean intrinsic color of the spheroidal component derived from the new observations of the bulge (corrected for interstellar extinction and scattering) is $\langle B - V\rangle_I$ = 0.65 ± 0.05, in close agreement with previous estimates (Arp 1965); the mean color of the disk stellar population derived from local luminosity functions is $\langle B - V\rangle_{II}$ = 0.40 (after Holmberg 1950, transformed to B,V system). In the face-on view a uniform absorbing layer with A_B = 0.4 mag produces a color excess E(B - V) = 0.039 mag and the total color index of the Galaxy for an external observer is $(B - V)_T$ = 0.53 ± 0.05, in fair agreement with the average values 0.57 for Sbc and 0.51 for Sc galaxies (de Vaucouleurs 1977a).

The hydrogen index HI implied by the luminosity index $\Lambda = 0.71$ and the statistical relation $\langle HI \rangle = 1.65 - 1.30(\Lambda - 1)$ (de Vaucouleurs 1977a) is HI = 2.03 which by definition of the hydrogen index corresponds to a logarithmic ratio of the neutral hydrogen mass $\mathfrak{M}_H$ to the face-on B luminosity (both in solar units) $\log \mathfrak{M}_H/\mathcal{L}_B = -0.02 - 0.4(HI) = -0.83$. With $M_T^o = -20.08$, this implies a total HI mass $\mathfrak{M}_H = 2.32.10^9 \mathfrak{M}_\odot$.

The HI mass in the disk within $r = 1.5\ r_o$ is $M_H(r < 1.5\ r_o) = 1.66.10^9 \mathfrak{M}_\odot$ or 71% of the total (after Baker and Burton 1975, scaled down from $r_o = 10$ kpc to $r_o = 8$ kpc); this leaves $0.66.10^9 \mathfrak{M}_\odot$ of atomic hydrogen or 29% of the total to be distributed in the warped disk at $r > 1.5\ r_o = 12$ kpc and in the galactic corona, which appears very reasonable.

With the total mass of the Galaxy derived from the HI rotation curve (Schmidt 1965) and from the velocity dispersion of globular clusters (de Vaucouleurs 1977b) $\mathfrak{M}_T \simeq 2.10^{11} \mathfrak{M}_\odot$ (for $r_o = 8.0$ kpc), the mass-luminosity ratio is $\mathfrak{M}_T/\mathcal{L}_B = 12.5$ (solar units), and the HI mass fraction is $\mathfrak{M}_H/\mathfrak{M}_T = 0.012$. The total hydrogen fraction (including ionized and molecular) may be about 2 to 2.5%.

In conclusion, our Galaxy appears to be a normal giant, multi-arm spiral of type SAB(rs)bc II, total absolute magnitude -20.1(B), -20.6_5(V) and effective diameter 10 kpc, if $r_o = 8.0$ kpc. It is in many respects similar to NGC 1073, 4303, 5921 and 6744 (for illustrations see de Vaucouleurs 1970). The average of these four galaxies is in remarkably close agreement with the photometric properties of the Galaxy. The main results are summarized in Table I; a more detailed report will appear in the Astronomical Journal. This work was supported in part by the National Science Foundation under Grant AST 75-22900.

TABLE I
Photometric Parameters of the Galaxy and of Average of Four Spirals†

Parameter		Average	Galaxy
Isophotal diameter, D_o	(kpc)	22.7	23.0
Effective diameter, D_e	"	10.3	10.2
Inner ring diameter, D(r)	"	5.75	6.:
Absolute B magnitude, M_T^o		-20.0	-20.1
Color index, $(B - V)_T^o$		0.51	0.53
Spheroidal fraction, k_I(B)		(0.33)+	0.34
Luminosity index, Λ		0.67	0.71
Mean effective surface brightness*, m_e'		22.08	22.06

†NGC 1073, SB(rs)c II; NGC 4303, SAB(rs)bc I; NGC 5921, SB(rs)bc I-II; NGC 6744, SAB(r)bc II. +NGC 6744 only. *B mag sec^{-2}.

REFERENCES

Arp, H. C. 1965, Astrophys. J., 141, 43.
Baade, W. 1951, Publ. Univ. Michigan Obs., X, 16.
Baker, P. L., Burton, W. B. 1975, Astrophys. J., 198, 281.
Becker, W. 1964, Z. Astrophys., 58, 202.
Courtès, G. 1972, in *Vistas in Astronomy*, 14, 140.
de Vaucouleurs, G. 1958, Astrophys. J., 128, 465.
de Vaucouleurs, G. 1959, in *Handbuch der Physik*, Vol. 53, 275.
de Vaucouleurs, G. 1962, in IAU Symp. no. 15, 1.
de Vaucouleurs, G. 1963, Astrophys. J. Suppl., 8, no. 74, 31.
de Vaucouleurs, G. 1964, in IAU Symp. no. 20, 88.
de Vaucouleurs, G. 1970, in IAU Symp. no. 38, 18.
de Vaucouleurs, G. 1974, in IAU Symp. no. 58, 1.
de Vaucouleurs, G. 1977a, in *The Evolution of Galaxies and Stellar Populations*, Yale Univ. Obs., 43.
de Vaucouleurs, G. 1977b, Astron. J., 82, 456.
de Vaucouleurs, G. 1978a, Astrophys. J., 223, in press.
de Vaucouleurs, G. 1978b, Astrophys. J., 224, in press.
de Vaucouleurs, G. 1978c, Astrophys. J., 224, in press.
de Vaucouleurs, G. 1978d, Astrophys. J., submitted.
de Vaucouleurs, G., Buta, R. 1978, Astron. J., submitted.
Freeman, K. C. 1970, Astrophys. J., 160, 811.
Georgelin, Y. M., Georgelin, Y. P. 1976, Astron. Astrophys., 49, 57.
Holmberg, E. 1950, Medd. Lunds Obs., II, no. 128, 44.
Kerr, F. J. 1967, in IAU Symp. no. 31, 239.
Kerr, F. J. 1969, in Ann. Rev. Astron. Astrophys., 7, 39.
Kerr, F. J. 1970, in IAU Symp. no. 38, 95.
Kerr, F. J., Westerhout, G. 1965, in *Stars and Stellar Systems*, V, 167.
Maihara, T., Oda, N., Sugiyama, T., Okuda, H. 1978, Publ. Astron. Soc. Japan, 30, 1.
Mills, B. Y. 1959, in IAU Symp. no. 9, 441.
Oort, J., Kerr, F. J., Westerhout, G. 1958, Monthly Notices Roy. Astron. Soc., 118, 379.
Pence, W. D. 1978, Univ. Texas Ph.D. thesis.
Peters, W. L. 1974, Astrophys. J., 195, 617.
Sandage, A. 1961, *The Hubble Atlas of Galaxies*.
Sandage, A. 1975, in *Stars and Stellar Systems*, IX, 1.
Schmidt, M. 1965, in *Stars and Stellar Systems*, V, 513.
Schmidt-Kaler, T., Schlosser, W. 1973, Astron. Astrophys. 29, 409.
Schweizer, F. 1976, Astrophys. J., 31, 313.
Simonson, S. C. 1976, Astron. Astrophys., 46, 261.
Simonson, S. C., Mader, G. L. 1973, Astron. Astrophys., 27, 337.

DISCUSSION

van den Bergh: Recently Tammann used $L = 4 \times 10^{10}\ L_{\odot}$ for the Galaxy to obtain a mean interval τ = 20 yr between galactic supernova outbursts. Lowering the galactic luminosity to $L = 1.7 \times 10^{10}\ L_{\odot}$, as you have just suggested, would increase τ to a (perhaps more comfortable!) 50 years.

https://doi.org/10.1017/S0074180900014480 Published online by Cambridge University Press

Schmidt-Kaler: I completely agree with the type Sbc in your system of classification for our Galaxy. But I wonder about the luminosity class: from the size, we find about $R_H \cong 15$ kpc or a little more (if $R_{\odot}$ = 8 kpc); from the maximum rotation velocity, $v_m \cong 250$ km/s.

de Vaucouleurs: The Holmberg radius is 17 kpc in our mode; the luminosity class is derived mainly from the total absolute magnitude and from our re-calibration of luminosity classes. With all the uncertainties in photometry, calibrations, etc., a 12% difference is not significant.

Basu: What is the distance of the Inner Lindblad Resonance in your model of our Galaxy.

de Vaucouleurs: I don't know. Can one of the theorists present tell us?

Contopoulos: It is about 3.5 kpc (for R_o = 10 kpc), essentially independent of the model adopted.

Miller: I should like to comment on the interpretation of numbers such as the distance to the Galactic center, and to pose a question for the observers. Is our Galaxy axisymmetric, as we usually assume in interpreting observations, or might it be elongated, possibly as far as a 2:1 axis ratio? The background to this question is as follows. In self-consistent N-body experiments we typically find a prolate bar that rotates end-over-end in space. An elliptical galaxy flatter than E2 is probably prolate. The same situation must occur with S0's and ordinary spirals. With spirals, gas should settle into the equatorial plane and assume an elongated form. Gas streaming and the local standard of rest would move on elliptical tracks about the center of the galaxy. The velocity dispersion in these prolate forms is anisotropic, with the long axis parallel to the long axis of the elongated form. We can tentatively locate the Sun in such a system by noting the vertex deviation: the long axis of the velocity ellipsoid leads the motion of the local standard of rest. This would place the Sun some 10-15° away from the long axis in the direction of streaming. There would be a small K-term, but within observational limits. The streaming takes place within this elongated pattern as the pattern itself rotates. A spiral pattern might exist within this elongated outline just as it could within a circular outline. This possibility complicates Galactic models appreciably, and is unfortunate from that point of view. I would like to ask observers to tell me of observational evidence that forces us to treat the Galaxy as circular, or as nearly circular.

Burton: Deviations from axial symmetry are illustrated by systematic differences in the total extent of HI spectra measured at corresponding longitudes on either side of the Sun-center line. I have given such a plot in Figure 3 of P.A.S.P. 85, 679, and in Figure 4.7 of "Galactic and Extragalactic Radio Astronomy" (Verschuur and Kellermann, eds.). There are trends that could be interpreted in terms of an overall elongated form. In addition, it is interesting in this regard that the $b = 0°$ v,ℓ diagram is pinched closer to $v = 0$ km s^{-1} at $\ell = 186°$ than at $\ell = 180°$.