

Distribution of Stars in the Draco Dwarf Galaxy

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Star counts on 12 plates of the nearby dwarf galaxy in Draco provide information on the structure of the system. It is elliptical in outline, with an ellipticity averaging $\epsilon=0.29\pm0.04$. The projected density profile looks very much like that for other dwarf elliptical galaxies, and agrees very well with King's empirical formula. A cutoff radius is detected at a distance of $26'\pm2'$. This corresponds to a linear radius of 0.51 ± 0.04 kpc. The computed tidal limit for the system is 0.41 kpc, in good agreement with the observed size.

I. INTRODUCTION

THIS is the last in a series of papers that explore the problem of the structure of local group dwarf elliptical galaxies by means of star counts. Other papers dealt with the Fornax, Sculptor, Leo I, Leo II, and Ursa Minor Dwarfs (Hodge 1961a, 1961b, 1962, 1963, 1964a).

The Draco dwarf galaxy, discovered by Wilson (1955), was extensively studied by Baade and Swope (1961). The latter astronomers measured the color-magnitude diagram of the system and examined its variable star population in great detail.

Baade and Swope's photometry provides a reliable distance to the Draco dwarf. They found that the magnitude at mean luminosity for the RR Lyrae variables is 20.48 in B . From their color-magnitude diagram the mean color of these variables can be estimated to be $B-V=0.40$. Using an absolute magnitude for RR Lyrae variables of $+0.5$ in V , the apparent modulus of the Draco system is 19.58. The galactic latitude of Draco is 34.6° , so that the absorption calculated from the cosecant law using a constant of 0.25 is 0.44. Thus the true modulus of Draco must be 19.14, implying a linear distance of 68 kpc.

The galaxy contains no globular clusters or obvious nebulae and galaxies are conspicuous right up to the center of the system, indicating that it also contains little or no dust. Its total magnitude has never been measured.

II. OBSERVATIONAL DATA

Table I lists the 12 plates used in this study for star counting. All of the 200-in. plates and one of the Schmidt (PS 1698) were taken by Baade in the process of his study, and were kindly counted by Miss Swope. The remainder of the plates were taken expressly for this investigation. The table lists the background density for each plate in the cases where this background could be established unambiguously. The field of the 200-in.

TABLE I. Observational material.

Plate	Telescope	Emulsion (Kodak)	Filter (Schott)	Exposure (min)	Background density (stars per square minute)	Plate limit (mag.)
PH 1031	200 in.	103a-O	GG1	20	...	~ 22.8
PH 1249	200 in.	103a-O	GG1	20	...	~ 22.4
PH 1250	200 in.	103a-O	GG1	20	...	~ 22.4
PH 1251	200 in.	103a-O	GG1	20	...	~ 22.4
PH 1263	200 in.	103a-O	GG1	20	...	~ 22.4
PH 1459	200 in.	103a-O	GG13	20	...	~ 22.4
PH 1460	200 in.	103a-O	GG13	20	...	~ 22.4
PH 1461	200 in.	103a-O	GG13	20	...	~ 22.4
PH 1707	200 in.	103a-O	GG1	20	...	~ 22.4
ED 1778	120 in.	103a-O	GG13	30	0.15 ± 0.05	~ 22.0
ED 1778 ^a	120 in.	103a-O	GG13	30	0.19 ± 0.05	~ 22.0
ED 1778 ^b	120 in.	103a-O	GG13	30	0.17 ± 0.05	~ 22.0
PS 1698	48 in.	103a-O	none	10	0.95 ± 0.09	~ 21.0
PS 1698 ^a	48 in.	103a-O	none	10	1.12 ± 0.05	~ 21.0
PS 5533	48 in.	103a-D	yellow	15	1.27 ± 0.10	~ 20.0
PS 5534	48 in.	103a-D	yellow	12	1.14 ± 0.09	~ 20.0

^a Second independent counting.

^b Third independent counting.

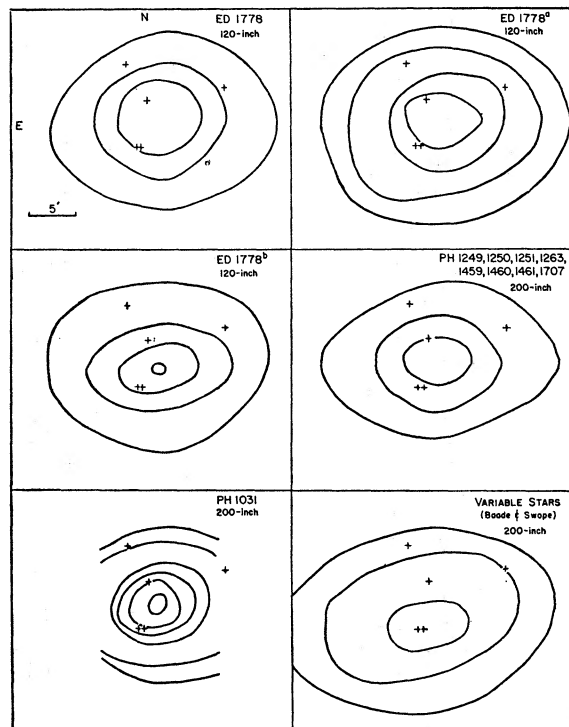


FIG. 1. Contour diagrams for star counts on 200-in. and 120-in. telescope plates. The diagram for the RR Lyrae variables was drawn from Baade and Swope's published chart.

TABLE II. Projected density.^o

r	ED 1778		ED 1778 ^a		ED 1778 ^b		PS 1698		PS 1698 ^a		PS 5533		PS 5534		Mean profile	p.e.
	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.		
1.5	11.99	11.99	10.29	9.56	13.63	11.73									11.09	.73
2.0	9.48	9.49	9.28	8.62	11.55	9.94	5.97	11.15	5.68	9.68	10.14	12.62	5.36	10.74	10.32	.81Y
2.5	9.35	9.35	9.44	8.77	11.49	9.89									9.34	.38Y
3.0	8.08	8.08	9.71	9.02	10.42	8.97									8.69	.29Y
3.5	10.76	10.76	9.12	8.47	9.30	8.01									9.08	.80Y
4.0	8.68	8.68	8.81	8.18	9.67	8.31	4.66	8.70	5.60	9.54	6.09	7.58	4.53	9.08	8.58	.39
4.5	8.08	8.08	7.62	7.08	8.39	7.22									7.46	.29
5.0	6.43	6.43	6.28	5.83	7.64	6.58									6.28	.21
5.5	6.48	6.48	6.93	6.44	5.88	5.06									5.99	.44
6.0	5.36	5.36	6.18	5.74	6.52	5.61	3.10	5.79	3.25	5.54	4.80	5.98	3.11	6.23	5.75	.17
6.5	4.02	4.02	6.12	5.69	6.68	5.75									5.15	.52
7.0	4.56	4.56	5.64	5.24	4.97	4.28									4.69	.27
7.5	4.77	4.77	4.84	4.50	4.86	4.18									4.48	.15
8.0	4.29	4.29	3.61	3.35	4.38	3.77	1.94	3.62	2.39	4.07	2.89	3.60	1.68	3.37	3.72	.21
8.5	3.65	3.65	4.30	3.99	4.00	3.44									3.69	.15
9.0	3.06	3.06	3.72	3.46	4.00	3.44									3.32	.11
9.5	3.06	3.06	3.98	3.70	4.43	3.81									3.52	.22
10.0	3.17	3.17	3.45	3.21	3.47	2.99	1.76	3.29	1.76	3.00	2.39	2.98	1.53	3.07	3.10	.07
10.5	3.32	3.32	2.81	2.61	3.15	2.71									2.88	.24
11.0	2.69	2.69	3.45	3.21	3.47	2.99									2.96	.13
11.5	2.69	2.69	4.93	4.58	3.04	2.62									3.30	.61
12.0	2.36	2.36	2.81	2.61	2.56	2.20	1.05	1.96	1.56	2.66	1.73	2.15	1.35	2.71	2.38	.17
12.5	2.04	2.04	1.90	1.77	1.97	1.70									1.84	.38
13.0	1.83	1.83	2.16	2.01	2.34	2.01									1.95	.03
13.5	1.56	1.56	2.06	1.91	2.40	2.07									1.85	.13
14.0	1.51	1.51	1.52	1.41	2.08	1.79	.61	1.14	.74	1.26	.61	.76	.27	.54	1.20	.27
14.5	1.29	1.29	1.52	1.41	1.76	1.52									1.41	.05
15.0	.97	.97	1.79	1.66	1.92	1.65									1.43	.07
15.5	1.03	1.03	1.74	1.62	1.92	1.65									1.43	.19
16.0	1.13	1.13	1.42	1.32	1.81	1.56	.41	.77	.44	.75	.51	.63	.48	.96	1.02	.20
16.5	1.13	1.13	1.52	1.41	1.38	1.19									1.24	.11
17.0	.81	.81	1.31	1.22	1.17	1.01									1.10	.13
17.5	.65	.65	.77	.72	.79	.68									.68	.02
18.0	.81	.81	1.09	1.01	.85	.73	.19	.35	.17	.29	.39	.49	.04	.08	.54	.21
18.5	.87	.87	.77	.72	.85	.73									.77	.05
19.0	.87	.87	.83	.77	1.01	.87									.84	.03
20.0							-.06	-.11	.17	.29	.13	.16	0.0	0.0	.09	.10
22.0							.06	.11	-.07	-.12	.13	.16	-.02	-.04	.03	.08
24.0							.01	.02	-.04	-.07	.16	.20	0.0	0.0	.04	.07
26.0							.08	.15	-.05	-.09	.09	.11	-.06	.12	.07	.07
28.0							.10	.19	.10	.17	.05	.06	.01	-.02	.10	.05
30.0							.12	.22	.02	.03	.09	.11	.11	.22	.15	.05
32.0							-.01	-.02	0.0	0.0	-.02	-.02	.04	.08	.01	.07
34.0							-.06	-.11	.02	.03	-.03	-.04	-.11	-.22	-.09	.01
36.0							-.11	-.21	-.09	-.15	-.07	-.09	-.13	-.26	-.18	.01
38.0							.01	.02	-.09	-.15	.02	.02	.17	.34	.06	.11
40.0							-.16	-.30	.07	.12	-.01	-.01	.15	.30	.03	.13

^{a,b} Same as in Table I.^o Stars per square minute of arc; background subtracted.

telescope was too small for purposes of establishing the background. Therefore, the 200-in. plates could not be used to provide density profiles, but were nevertheless very useful for helping to establish the shape of the system. Eight of the 200-in. plates listed were taken at different locations across the Draco system and were found by Miss Swope to be nearly uniform in the limiting magnitude reached. These have been combined to form a single contour diagram (see next section), but they were not used for determining density profiles because of the large errors that could be introduced by slight differences in the limiting magnitude. A 1 mm rectangular grid was used for counting the 200-in. and 48-in. plates and a 2 mm grid for the 120-in. plate. All counts were to the limit of the plates. One Schmidt

plate was counted independently by two persons and the 120-in. plate was counted independently by three persons. Systematic differences between persons' counts were found to be appreciable, but smaller than the systematic differences between plates after normalization (see Table II).

III. DISTRIBUTION OF STARS

Lines of Equidensity

Figures 1 and 2 show contour diagrams drawn through the counts of the Draco galaxy. There is no evidence for any asymmetry or irregularity in the distribution of stars of the system. The ordinary stars seem to be distributed similarly to the RR Lyrae

variables (Fig. 1), as nearly as can be judged from the small number of the latter.

Shape

The ellipticity (defined by $\epsilon=1-b/a$), was derived from the contour diagrams shown in Figs. 1 and 2. There is no evidence for variation of ellipticity with distance from the center of the system. The data provide a mean ellipticity of $\epsilon=0.29\pm0.04$.

Orientation

The mean orientation for all contour lines in all of the contour diagrams of Figs. 1 and 2 provides an orientation for the system, which has a major axis lying in position angle $84^\circ\pm3^\circ$.

Density Profiles

Table II provides a summary of the results of the counts on all plates for which reliable background densities could be estimated. The star densities for each plate were obtained by averaging the counted star density along an elliptical line with orientation and shape as determined above. Thus the quoted major axis profile is in reality an integrated profile over the entire system, reduced to the scale of the major axis. The background has been subtracted in all cases in Table II. For the 120-in. telescope plate, the counts do not reach beyond the boundaries of the galaxy. It is possible that the background density estimated for that plate is slightly in error because of this.

In order for all of the counts to be combined to provide a mean profile, individual counts were normalized to agree with a total star density for the first

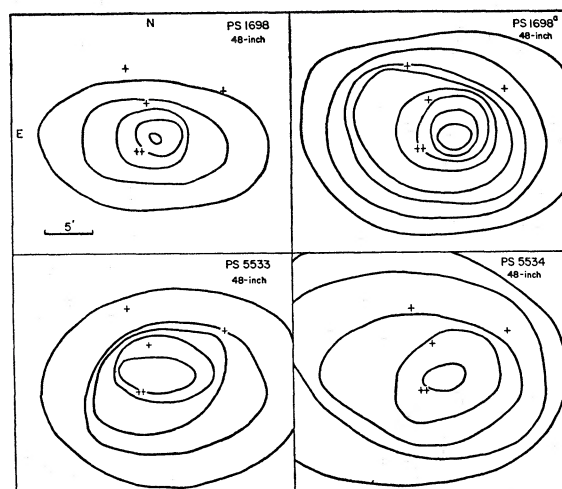


FIG. 2. Contour diagrams for star counts on Schmidt plates.

counting of plate ED 1778. A mean of these normalized counts is given in Table II, along with the computed probable error for the mean. Figure 3 displays the mean profile.

Radius

Following King (1962), the radius of the Draco system is estimated by means of his semiempirical density formula in which a tidal cutoff radius is implicit. Figure 4 shows a plot of $n^{1/3}$ against $1/r$ for the outer portion of the Draco system. This provides a value for the cutoff radius r_t as well as a test for agreement in the outer portion with King's formula. The points fall close to a straight line, indicating good agreement. A least-squares solution from Fig. 4 leads to a value for the cutoff radius of 29.5 ± 5.8 . However, because of the

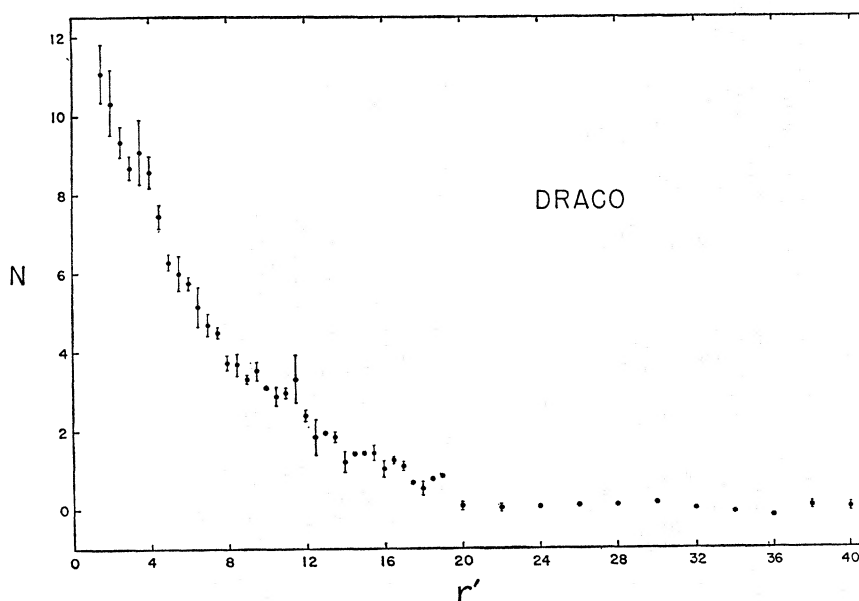


FIG. 3. Major axis profile of the Draco galaxy, plotted from the mean values of Table II. Background stars have been subtracted. Probable errors (not including that of background count) are indicated.

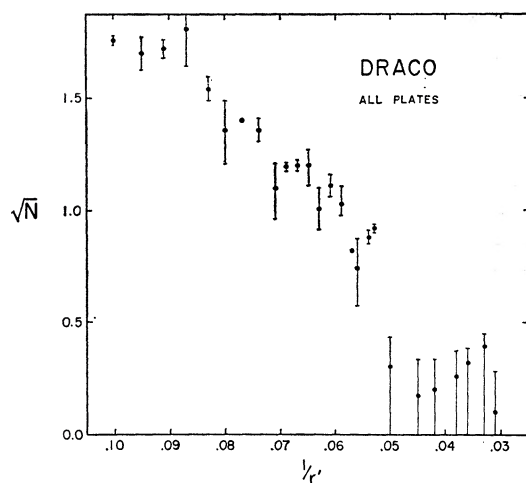


FIG. 4. Plot for determining cutoff radius counts on all plates.

uncertainty in the background density for the plate ED 1778, this value is possibly systematically in error. Figure 5 shows a similar plot for the Schmidt plates only, more reliable because of the certainty of the background densities for the Schmidt plates. From Fig. 5 the radius is found to be $25'.6 \pm 1'.8$. The adopted radius is $26' \pm 2'$, which for a linear distance of 68 kpc, is equivalent to a linear radius $0.51 \text{ kpc} \pm 0.04 \text{ kpc}$. Thus the Draco system is intrinsically the smallest galaxy in the local group.

IV. COMPARISON WITH OTHER GALAXIES

Figures 6 and 7 illustrate a comparison between the density determined for the Draco system and the interpolation formulas for giant elliptical galaxies proposed by Hubble (1930) and de Vaucouleurs (1948), respectively. The disagreement is in the same sense

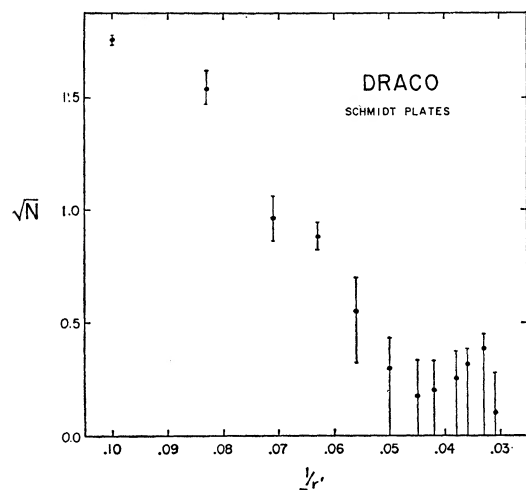


FIG. 5. Plot for determining cutoff radius from counts on Schmidt plates only.

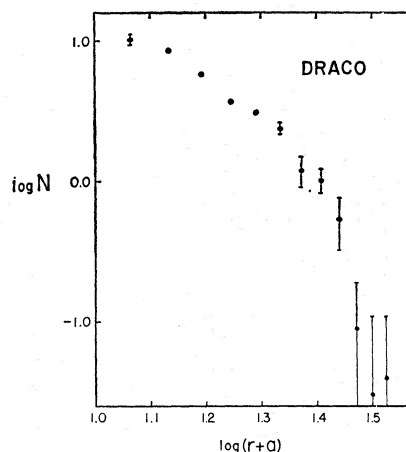


FIG. 6. Plot of counts in plane in which Hubble's interpolation formula forms a straight line.

as found previously for other dwarf ellipticals; namely, the observed densities fall off faster in the outer regions than predicted. Figure 8 shows a comparison with King's empirical formula in which the tidal effects are included. The excellent agreement suggests strongly that the outer portions of the profile are tidally determined.

V. GRAVITATIONAL RADIUS

The predicted gravitational radius for the system can be computed from von Hoerner's (1957) formula

$$r = R_g (m/3M_g)^{1/3},$$

where m is the mass of the satellite galaxy, M_g is the mass of our galaxy, and R_g is the distance from our galaxy to the satellite galaxy.

The mass of the Draco system can be computed from the comparison of its luminosity function with that of

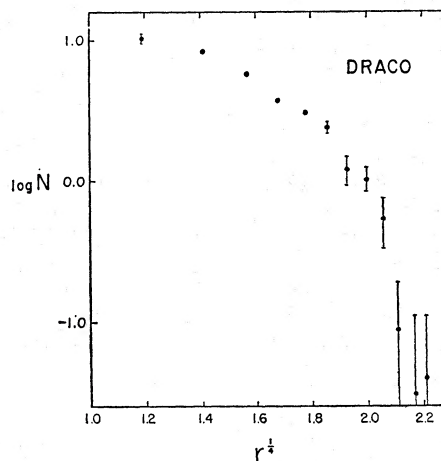


FIG. 7. Plot of counts in plane in which de Vaucouleur's interpolation formula forms a straight line.

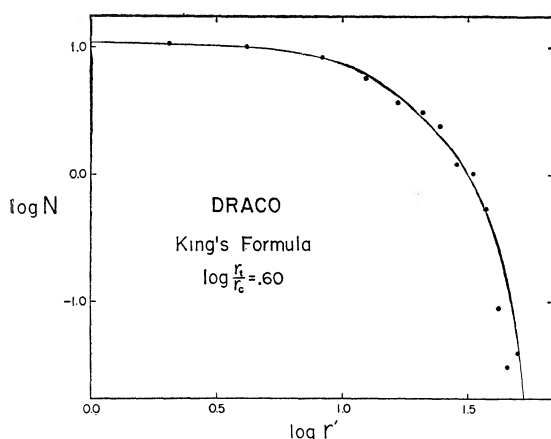


FIG. 8. Comparison of counts with King's empirical formula, with tidal radius implicitly included.

M3. From Miss Swope's counts on plate PS 1698, which had a limiting magnitude of $m_B = 21.0$, there are 969 member stars (3950 stars counted of which 2981 are background). This limit is equivalent to $M_B = +1.1$. For M3 (Sandage 1954), there are 1117 stars to $M_{pg} = +1.1$. Therefore, the mass ratio for Draco/M3 is 0.87. If we adopt for the mass of M3 a value of $1.4 \times 10^5 M_\odot$ (Sandage 1954), then we find that the mass of Draco is approximately $M = 1.2 \times 10^5 M_\odot$. Implicit in this calculation is the assumption that the luminosity functions for the two systems are everywhere the same.

With this adopted value for the mass of Draco and

with a mass for our Galaxy of $2 \times 10^{11} M_\odot$ (Brandt 1960), we predict a tidal radius for the Draco system of 0.41 kpc. This value is very close to the observed cutoff radius of the system, 0.51 kpc. A discussion of the possible significance of the observed tidal radii of dwarf galaxies of the local group is given elsewhere (Hodge 1964b).

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