

Note on Planetary Nebulae in M 31

LITTLE can be added to Baade's report (1955) on five planetary nebulae that he found in Field IV in M31. They have been marked on the chart (Plate I of the preceding paper) and are numbered using a prefix PL. Table I lists new magnitudes for them based on

TABLE I.

	<i>B</i>	<i>V</i>	<i>B</i> − <i>V</i>	<i>M_B</i>
PL 1	22.2:	...	...	−2.65
2	22.2	21.5	+0.7	2.65
4	22.4	21.3	+1.1	2.35
5	22.3	21.7	+0.6	2.55
6	22.3	21.0	+1.3	−2.55
Mean	22.3	21.4	+0.9	−2.55

Arp's photoelectric sequence and measured in the same way as the variables. The apparent magnitudes are uncorrected for reddening.

Both the *B* and *V* magnitudes are very sensitive to whether the emission lines are included or cut off by the combination of plate and filter used. The conversion of these *B* magnitudes to the International system used in planetary nebulae catalogues has not been attempted as the measured magnitudes are excitation dependent.

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Baade, W. 1955 *Astron J.* **60**, 151.

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Distribution of Stars in the Leo I Dwarf Galaxy

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The distribution of resolved stellar images in the dwarf galaxy Leo I has been determined from star counts on seven plates. The galaxy is elliptical in outline and perfectly symmetrical within the observational uncertainties. The ellipticity is approximately uniform from the center outwards with a value of ϵ of 0.31 ± 0.07 . The star density profile of the Leo I system resembles those of other dwarf elliptical galaxies, and is unlike those for giant ellipticals. If the distance to the system is 230 kpc, then the observed sharp cutoff in radius at $14.3 \text{ min} \pm 1.0 \text{ min}$, along the major axis, corresponds to a linear cutoff radius of 0.95 ± 0.07 kpc. This is somewhat smaller than the computed present tidal radius.

I. INTRODUCTION

THE Leo I galaxy (Fig. 1) is the fourth object to be studied in an attempt to determine and understand the structure of dwarf elliptical galaxies. The three previous galaxies studied (Hodge 1961a, 1961b, 1962) were found to be remarkably similar in their structural properties. All showed a steeper profile than predicted by a Hubble luminosity law and all had a distinct cutoff at a distance near to, but somewhat smaller than what one predicts from tidal considerations. In the local group of galaxies the two most distant known dwarf ellipticals are the Leo I and Leo II systems discovered in 1950 (Harrington and Wilson 1950). Leo I, although brighter than Leo II, has not been extensively studied because of its proximity to the star Regulus, which makes photography of the system difficult for large telescopes with correcting lenses. Baade (1950) obtained a few plates of it with the 200-inch telescope, using diaphragms in the optics to cut down reflections from Regulus. He estimated that the distance to the galaxy is about the same as that of the

Leo II system, for which Sandage (1961) quotes a distance modulus of $m - M = 21.8$, corresponding to 230 kpc. Baade found a few RR Lyrae variables, and no evidence for globular clusters or dust or gas. Many RR Lyrae variables have been found at Berkeley using 120-inch plates and these are presently being studied; periods and light curves are not yet available. There is a diffuse object near the major axis of Leo I, but this is apparently unrelated to the system; on the best 120-inch plates it has the appearance of a distant spiral galaxy. The total apparent magnitude of Leo I has been measured by Holmberg (1958), who finds $m_v = 10.40$ and $CI = +0.87$. The dimensions from Holmberg's data are 12.0 min by 9.5 min; these compare with Harrington and Wilson's estimate of a diameter of 17 min. Accepting a distance of 230 kpc leads to a value for the absolute visual magnitude of the system of $M_v = -11.4$, and the linear dimensions determined by Holmberg become 830 by 650 pc. Intrinsically Leo I is an exceedingly small, very faint object, though brighter by 1.5 mag. than Leo II.

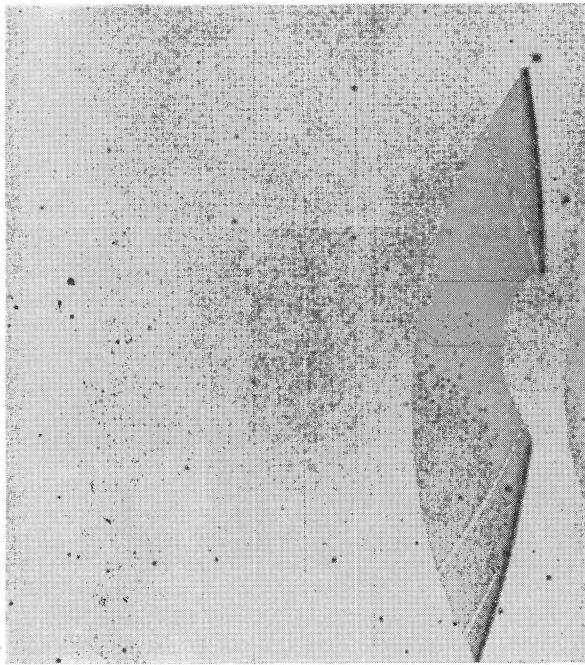


FIG. 1. Photograph of the Leo I galaxy taken with the 120-inch Lick Observatory reflector on 103aD emulsion behind a GG 11 filter. The ghost image of Regulus is conspicuous. North at right, east at bottom. Scale: $16''/\text{mm}$.

II. OBSERVATIONAL DATA

Although the luminosity density of the Leo I system is not as low as for other extreme dwarf galaxies, the most effective means of studying its structure is still by means of star counts on plates which resolve the system. For this purpose seven plates were used: one 200-inch plate taken by Baade and kindly lent to the author by Dr. I. S. Bowen, three plates taken with the 100-inch telescope diaphragmed to 58 inches to improve the field size, one taken with the 48-inch Schmidt, and three taken with the 120-inch telescope. Table I lists the plates and describes the emulsions, filters, exposures, counted area, and background densities for them. As for other systems, it was found that the stars were

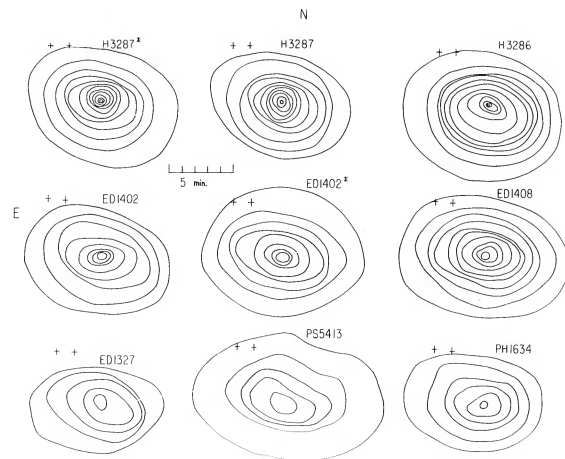


FIG. 2. Contour diagrams made directly from star counts, used to determine the shape and orientation of the Leo I system.

distributed similarly on plates taken in different colors.

A 1-mm rectangular grid was used for counting the Schmidt plate and a 2-mm grid for the others. All plates were counted to the plate limit and two of them were counted twice, by different persons. Systematic differences were found between the different counts on the same plates, but these differences were smaller than the differences between plates after normalization. Therefore, it is concluded that personal errors introduced are smaller than fluctuations from plate to plate.

III. DISTRIBUTION OF STARS

Lines of Equidensity

In order to determine the shape of the Leo I galaxy, contour diagrams were constructed for each set of counts. These contour diagrams, reproduced in Fig. 2, illustrate the great regularity and essentially perfect symmetry of the system.

Shape

Figure 3 illustrates the ellipticity of Leo I (defined by $\epsilon = 1 - b/a$), where it is shown that the ellipticity is

TABLE I. Observational material.

Plate	Telescope	Emulsion (Kodak)	Filter (Schott)	Exposure (min)	Counted area (square minutes)	Background density (stars per square minute)
PH 1634	200 inch	103a-O	GG1	20	340	2.68
ED 1327	120 inch	103a-O	GG13	40	450	1.04
ED 1402	120 inch	103a-D	GG11	45	480	0.85
ED 1402 ^a	120 inch	103a-D	GG11	45	720	0.92
ED 1408	120 inch	103a-O	GG13	45	480	1.58
H 3286	100 inch	103a-E	none	30	880	1.12
H 3287	100 inch	103a-D	GG11	45	1070	0.50
H 3287 ^a	100 inch	103a-D	GG11	45	680	0.94
PS 5413	48 inch	103a-E	red plexiglass	40	3150	0.61

^a Independent second counting to fainter limit.

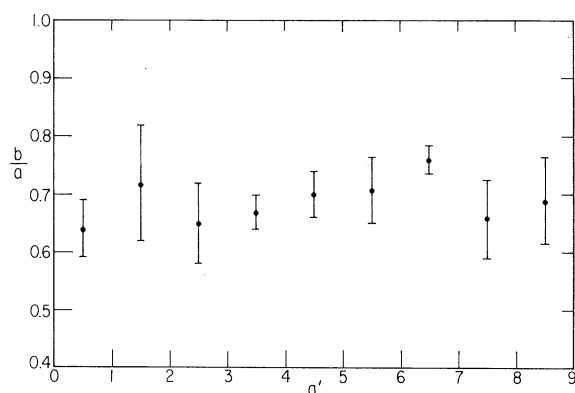


FIG. 3. The ratio of the axes measured from the contour diagrams plotted as a function of distance along the major axis. Probable errors are indicated.

apparently independent of the distance from the center of the system. The mean ellipticity found from the data is 0.31 ± 0.07 .

Density Profiles

Table II lists the projected star density for the Leo I system as a function of distance r along the major axis. These densities were obtained by means of averaging the observed counts on each plate along an elliptical line centered on the system with a major axis equal to the tabulated distance. In this way all of the counts for the entire face of the galaxy could be used to obtain a major axis profile, taking advantage of its symmetry and its known ellipticity. The tabulated measured projected densities are the difference between the actual average measured density and the background density

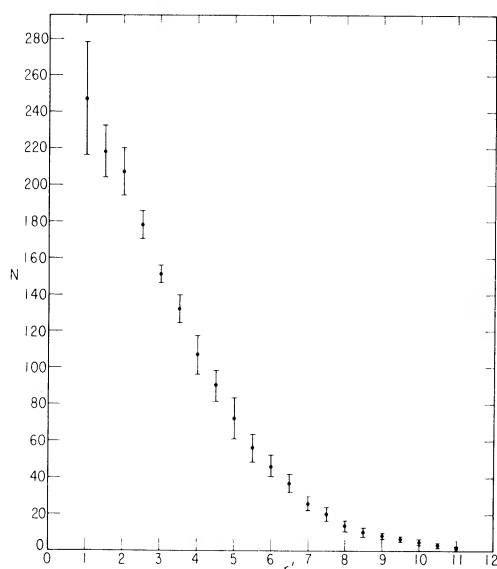


FIG. 4. Mean major axis profile of the Leo I system. Probable errors are indicated.

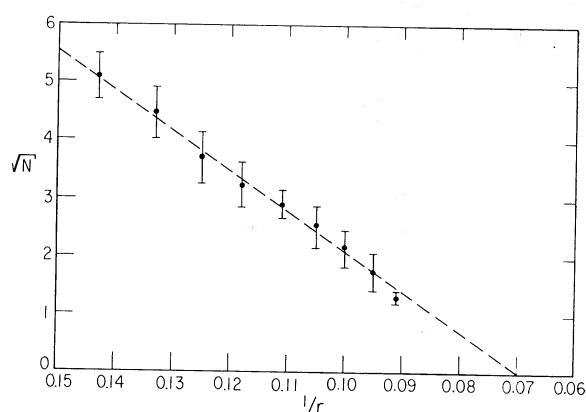


FIG. 5. Major axis profile plotted according to King's formula, used to determine the limiting radius.

listed in Table I. The densities given in Table II do not reach significantly beyond the boundaries of the Leo I system, but in all cases the background density was determined by counts at a sufficiently large distance from the tabulated limit to be reliable. Alternate columns in Table II list normalized projected densities, which were obtained by using plate ED 1408 as a standard and normalizing the remaining plates over the counted interval in common. A mean of the normalized density profiles was obtained by weighting the plates approximately according to the total number of stars counted on each. This mean is listed also in Table II and the probable error is given for each distance. The probable error is large near the center and small in the outer regions for two reasons: in the center the density of stars is sufficiently high so that counting errors are large, and in the outer regions the total number of stars and counting squares is large. Figure 4 gives a plot of the mean major axis profile, including probable errors for each point. The last column in Table II gives a smoothed profile, which is taken to be identical to the mean profile out to a distance along the major axis of 8 min, beyond which smoothing has been carried out.

Radius

Figure 5 illustrates the way in which the radius cutoff for the Leo I system can be determined by the assumption that King's (1962) semiempirical formula holds for the system. The plot of $n^{1/2}$ against $1/r$ serves to test agreement with King's formula and also to provide a value for the cutoff radius r_t . As the figure shows, the outer portion of Leo I plotted in this plane falls close to a straight line, indicating agreement with King's formula. A least-squares solution for the line is shown and a tidal radius r_t is derived to be 14.3 ± 1.0 . Assuming a distance of 230 kpc, we compute a linear radius for the Leo I system of 0.95 ± 0.07 kpc. Thus it is intermediate in intrinsic size between the Leo II system ($r = 0.8$ kpc) and the Sculptor system ($r = 1.1$ kpc).

TABLE II. Projected density.^a

<i>r</i>	ED 1327		ED 1408		ED 1402 ^b		ED 1402		PH 1634		H 3287 ^b		H 3287		H 3286		PS 5413		Mean prof.	p.e.	Smoothed profile
	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.	Meas.	Norm.			
1.0	75.4	272.4	191.4	191.4	107.8	270.3	57.7	209.7	140.3	250.0	29.4	285.7	26.9	341.1	32.4	265.2			246.6	±30.6	247
1.5	69.9	252.5	189.4	189.4	93.4	234.2	52.8	191.9	133.3	237.5									218.0	14.3	218
2.0	65.1	235.2	192.4	192.4	78.7	197.3	49.4	179.5	126.3	225.1	21.8	211.8	14.6	185.1	26.3	215.3	26.1	229.7	207.1	12.9	207
2.5	55.4	200.2	173.4	173.4	68.1	170.7	46.9	170.4	99.3	177.0									178.2	7.6	178
3.0	43.8	158.2	151.4	151.4	54.6	136.9	42.4	154.1	86.0	153.3	14.7	142.8	12.2	154.7	19.5	159.6			151.0	4.9	151
3.5	37.8	136.6	140.4	140.4	45.1	113.1	38.9	141.4	68.6	122.2	9.5	92.3	5.9	74.9	13.0	106.4	12.4	109.1	131.5	7.6	132
4.0	28.3	102.2	118.4	118.4	40.0	100.3	36.7	133.4	58.6	104.4									106.9	10.5	107
4.5	20.3	73.3	97.1	97.1	35.0	87.7	30.5	110.8	47.4	84.5	5.7	55.2	4.0	51.2	6.8	55.7			90.0	8.5	90
5.0	15.1	54.6	97.8	97.8	27.8	69.7	22.1	80.3	35.8	63.8									72.1	10.9	72
5.5	10.4	37.6	68.6	68.6	19.6	49.1	19.0	69.0	28.4	50.6	4.6	44.2	2.4	30.2	4.1	33.5	4.1	35.7	56.2	8.2	56
6.0	10.0	36.1	59.1	59.1	19.4	48.6	14.0	50.9	23.8	42.4									45.7	6.4	46
6.5	8.3	29.9	42.1	42.1	17.1	42.9	7.6	27.7	17.8	31.7	1.8	17.7	1.8	22.6	2.2	17.6			36.8	4.5	37
7.0	4.6	16.6	33.2	33.2	12.5	31.3	7.0	25.5	13.3	23.7									25.7	4.2	26
7.5	2.6	9.5	24.4	24.4	8.8	22.1	7.2	26.3	9.4	16.8									20.1	4.1	20
8.0	1.5	5.4	17.1	17.1	7.3	18.4	5.4	19.5	7.1	12.6	1.1	10.7	0.6	8.1	1.5	12.1	1.8	15.7	13.8	3.1	13.8
8.5	1.4	5.1	9.7	9.7	5.3	13.3	4.4	16.1	6.1	10.8									10.3	2.5	10.4
9.0	1.2	4.4	8.7	8.7	4.3	10.7	2.4	8.9			1.1	10.8	0.6	7.2	0.8	6.9			8.3	1.4	8.4
9.5	0.7	2.4	9.9	9.9	2.9	7.4	2.2	7.9			0.4	4.1	0.0	-0.1	0.4	3.0	0.3	2.6	7.4	1.9	6.4
10.0	0.2	0.9	5.7	5.7	2.1	5.3	1.5	5.6											3.9	1.4	4.7
10.5	-0.2	-0.6	2.4	2.4	1.3	3.3	1.1	4.0			0.2	1.9	0.2	3.0	0.3	2.5			2.1	1.2	3.1
11.0																			2.5	0.3	1.7
12.0																			-0.3		
14.0																			-0.1		
16.0																			-0.4		

^a Stars per square minute.
^b Independent second counting to fainter limit.

IV. COMPARISON WITH GIANT ELLIPTICAL GALAXIES

Figure 6 illustrates a comparison of the observed profile along the major axis of the Leo I system and the predicted profile derived by assumption of Hubble's luminosity distribution law for giant elliptical galaxies (1930). The agreement is poor, as has been found for all previously studied extreme dwarf ellipticals. Similarly, if the galaxy is compared to de Vaucouleurs' (1948) luminosity distribution law we again find rather poor agreement (Fig. 7). In fact, the two figures look very similar to corresponding figures obtained by comparison of the Leo II, Sculptor, and Fornax galaxies to these empirical laws.

V. GRAVITATIONAL RADIUS

Von Hoerner (1957) has shown that a cluster of small mass near a galaxy of large mass will have a limiting radius determined by the tidal action of the galaxy on the cluster. If it is assumed that the cluster has a circular orbit around the galaxy, the tidal radius can be calculated from the formula

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

where m is the mass of the cluster, M_g is the mass of the galaxy, and R_g is the distance from the galaxy to the cluster. To obtain an idea of the tidal limit imposed on Leo I by our galaxy, we must estimate the mass of the system. Since we as yet have no independent means of measuring the mass, we must assume a mass-to-light ratio. Because of the similarity of these dwarf elliptical galaxies to globular clusters (Baade and Swope 1961), the assumption can be made that the mass-to-light ratio for Leo I is like that of globular clusters, namely, approximately 2. Such an assumption leads to a value for the mass of $4 \times 10^6 M_\odot$, assuming Sandage's estimate of the distance and Holmberg's value for the photographic total magnitude. Now, using $1.8 \times 10^{11} M_\odot$ for the mass of the Galaxy (Brandt 1960), we predict a tidal radius for the Leo I system of 3.3 kpc. As for the Leo II system, this is approximately three times the

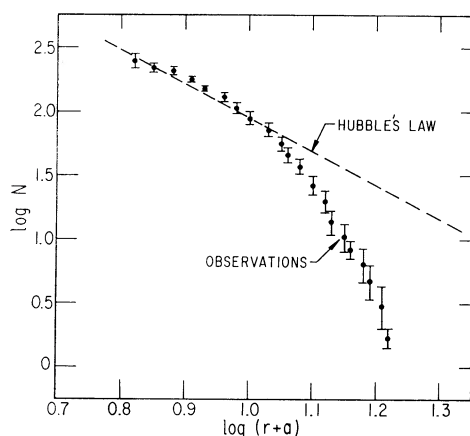


FIG. 6. Major axis profile plotted for comparison with Hubble's interpolation formula.

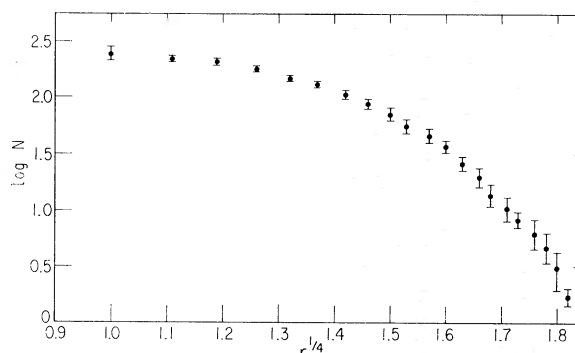


FIG. 7. Major axis profile plotted in units for which de Vaucouleurs' formula predicts a straight line.

observed cutoff value, and the explanation for the discrepancy is probably the same: the relaxation time for the system is sufficiently large so that we are observing a tidal effect which is the result of a much nearer encounter of the system with our galaxy. This view seems to be supported by the fact that the outer star distribution agrees well with the tidal hypothesis.

Certainly it must be admitted that the mass estimate and the distance estimate for the Leo I system are rough and preliminary. However, it is not believed that they are sufficiently uncertain to explain the discrepancy between computed and observed limiting radii. Instead the Leo I system seems to conform to the pattern found for the other three dwarf elliptical galaxies discussed in previous papers in this series, for which there was a similar correlation with the distance from our Galaxy. A discussion of this probable correlation will be postponed until the remaining dwarf systems have been analyzed.

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