SURFACE PHOTOMETRY OF SOUTHERN ELLIPTICAL NEBULAE

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Summary

Photometric measures of the surface brightness of a number of elliptical nebulae have been made. The isophotes determined are compared with the distribution of surface intensity found by Hubble in studies of elliptical nebulae. The same law is found to give a good general description of the brightness variation in the present case, but there are differences of detail which appear to be real, some of which suggest incipient development of spiral structures and the presence of differential rotation. Detailed discussion is deferred until material for the remaining bright southern elliptical nebulae is available.

Two previous studies in the field of surface photometry of nebulae by the present author have already appeared (**1**, **2**). The experience gained in this field emphasizes a number of points, one of which is the question of the particular class of astronomical object which can most fruitfully be studied by these methods. It seems of doubtful value merely to trace complex topographical detail, especially since, in a very real sense, a system of isophotes is less instructive than a series of photographs. Structures which are obvious in a photograph have a trick of disappearing from immediate view on an isophote map and, although more precise evidence of their form can be obtained by careful reading of the map, some skill is necessary to reconstruct the original picture from the latter. There is, however, the important advantage that photometric methods enable one to trace, with surprisingly little uncertainty, the forms of faint structures far beyond the limits detectable by visual inspection of plates, and farther still beyond the limits capable of reproduction on prints; but it is altogether a different matter to measure the surface brightness of such faint structures and to plot accurate isophotes.

A class of object which seems particularly likely to yield fruitful results is provided by the elliptical nebulae. The mode of variation of surface brightness is rather smooth, and seems to possess a certain generality which makes it particularly suitable for study by theoretical workers. There is now a fairly extensive literature dealing with surface photometry of elliptical nebulae in the northern sky (**3**, **4**, **5**, **6**, **7**, **8**).

The observations.—There are about 15 elliptical nebulae brighter than magnitude 12 and south of declination $-30°$. These fall into two groups on either side of the Milky Way. The present study deals with a group of seven objects in the region R.A. 3^{h}–$4^{h}\ 30^{m}$. The tables give data for these objects and of the plates used in this study. It will be seen that four of the objects are in pairs and that each pair can be photographed on one plate. One of these objects is NGC 1553 which is listed by Shapley and Ames (**9**) as type S (authority, plates

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from Bruce 24-inch refractor, exposure over 170 minutes), but it seems doubtful whether this can be correct. As we shall see, this particular object seems atypical, but, on photographic appearance, one would be strongly tempted to classify it as elliptical.

TABLE I

Nebulae Observed

Number	Position 1950		Magnitude (Shapley–Ames)	Type	Dimensions (Shapley–Ames)
	h m	° ′			′ ′
NGC 1291	3 15·5	−41 17	10·2	E	5·0×2·0
NGC 1344	3 26·7	−31 14	11·6	E	2·0×1·0
NGC 1380	3 34·6	−35 09	11·4	E	3·0×1·0
NGC 1399	3 36·6	−35 37	10·9	E	1·4×1·4
NGC 1404	3 37·0	−35 45	11·5	E	1·0×1·0
NGC 1549	4 14·7	−55 42	11·0	E	3·0×2·7
NGC 1553	4 15·2	−55 54	10·2	S	3·0×2·5

TABLE II

Selected Plates Reduced

Number	Emulsion	Exposure	Date 1950 Feb.	Object
		m		
A 660	I.A.Z.	15	14	NGC 1399, NGC 1404
A 661	I.A.Z.	15	14	NGC 1549
A 673	103a–O	9	17	NGC 1291
A 674	103a–O	9	17	NGC 1344
A 679	103a–O	15	18	NGC 1291
A 681	103a–O	15	18	NGC 1380
A 682	103a–O	15	18	NGC 1399, NGC 1404
A 683	103a–O	15	18	NGC 1549, NGC 1553

I.A.Z. = Ilford Astronomical Zenith.
103a–O = Kodak 103a–O.

The plates were all calibrated on a new tube sensitometer specially designed for the work. This gave 28 calibration spots imprinted on clear glass. The range covered was more than five magnitudes and an additional adjustment allowed the intensities to be moved up or down as a group to secure the best results for different emulsions.

The measurement and reduction were carried out in the usual way. The nebular images were run through every 0·25 mm. and runs on to clear glass were made every millimetre. Several "extinction" readings were secured on each run. Several checks, such as are afforded by running different plates in perpendicular directions through the microphotometer were made (*cf.* Evans (**1**)).

The sky background.—The results were then corrected for the background light of the sky. The mathematics of this situation are very simple.

We denote by L the total incident intensity at any point and partition this between L_0, the background luminosity, and L_t, the true intensity arising from the nebula. In terms of magnitudes these values are denoted by m, with corresponding suffixes.

Then $$L = L_t + L_0,$$
leading to $$m_0 - m = 2{\cdot}5 \log_{10}(1 + 10^{0{\cdot}4\,(m_0 - m_t)}).$$

This can be graphed (Fig. 1) and the resulting curve is used for applying background corrections.

It is also of interest to determine by how much a determined value of m_t derived from a given m will be affected by uncertainty in m_0. This we find from

$$\frac{dm_t}{dm_0} = -(10^{0 \cdot 4(m_0 - m)} - 1)^{-1},$$

which is also graphed. The error in determining m is usually of the order of $\pm 0 \cdot 02$ magnitude, but since m_0 usually lies on the toe of the curve, the error in

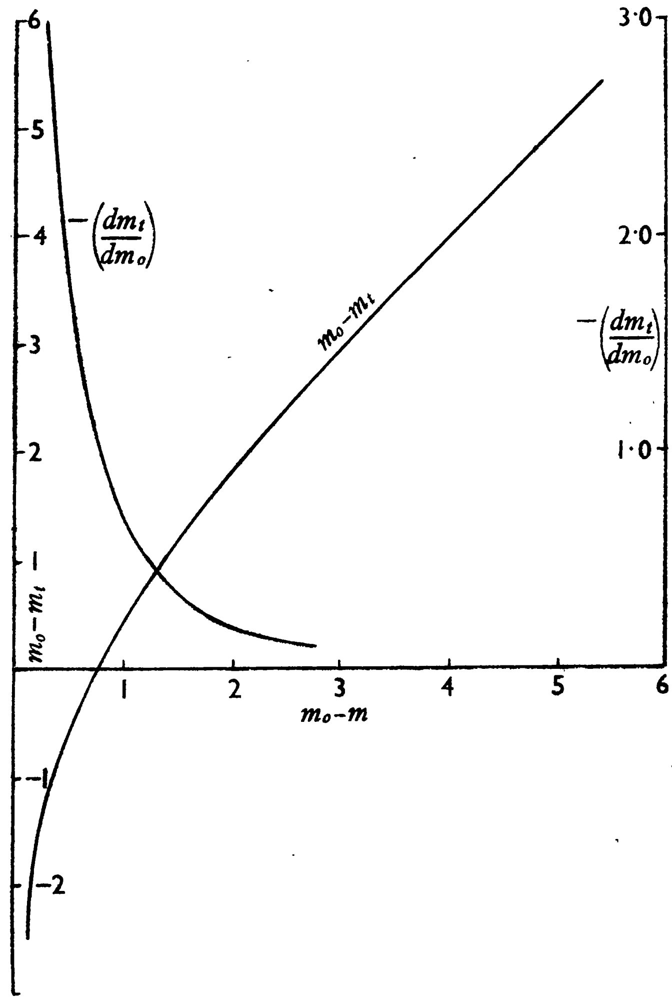


FIG. 1.—*The mathematics of background light.*

determining the latter may rise to the order of $\pm 0 \cdot 15$ magnitude. The error in fixing m_t due to uncertainty in m_0 will have the value

$$|\Delta m_t| = \frac{dm_t}{dm_0} |\Delta m_0|.$$

Suppose $|\Delta m_0| = 0 \cdot 10$ magnitude, then Δm_t will have the value 0·02 if $m_0 - m = 2 \cdot 0$, i.e. the error in finding m_t, due to uncertainty in fixing the background, will be no greater than the error of measurement of m itself if the total intensity is two magnitudes above background intensity. For differences of one magnitude and 0·5 magnitude the corresponding values of Δm_t are 0·07 and 0·17 magnitude respectively.

If the background is more intense, so that the point corresponding to m_0 falls on the straight line part of the characteristic curve, Δm_0 will fall to the ordinary error of measurement of a magnitude, which, doing rather less than justice to the measures, we have taken as $\pm 0{\cdot}02$ magnitude. If the background intensity is low, the point corresponding to m_0 falls to the toe of the characteristic curve where measures become unreliable, so that Δm_0 increases.

In practice, of course, measures will not be taken too close to the background, but it should be clear from the foregoing remarks that the presence of a weak and, hence, rather indeterminate background intensity can seriously affect the accuracy of determination of the true intensity, m_t, even when the measured brightness is well above the background.

In the course of the work a need was felt for a rough numerical measure of the reliability of each isophote as determined. This is especially necessary when isophotes derived from two plates are to be combined. This need was met by assigning to each isophote on a single plate a figure of merit, this figure being the product of two factors. The first factor is based on the value of Δm_t as given by the equation above. This depends first on the value of dm_t/dm_0 read off from the curve of Fig. 1, and secondly on the value of Δm_0, which is derived from the scatter of the values of the various runs on to parts of the plate remote from the nebular image. A maximum value of unity was assigned to this factor when Δm_t was $0{\cdot}02$ magnitude or less. For larger errors the value is proportionately reduced.

The second factor in the figure of merit is given the value unity when the observed value of m corresponds to a point on the straight line part of a characteristic curve, and is reduced proportionately to the slope of the part of the curve actually used. The product of the two factors gives the final figure of merit for each isophote determined from a given plate. In combining plates the figures are added. This system is entirely empirical. Its usefulness lies chiefly in the fact that when isophotes from different plates are being combined and a discrepancy arises, one can at once estimate the relative reliability of the individual determinations.

The curves of Fig. 1 have proved of great utility in a variety of connections. Consider, for example, the question of the circumstances in which it is permissible to ignore the sky background altogether. This will be the case when $m_0 - m$ and $m_0 - m_t$ are indistinguishable. This is not even the case when $m_0 - m$ is as great as three magnitudes, for then $m_t - m = 0{\cdot}07$. When $m_0 - m$ has the values $2{\cdot}0$ and $1{\cdot}5$, the corresponding errors are $0{\cdot}19$ and $0{\cdot}31$ magnitude respectively.

It may be thought that liability to error in a case where there is no detectable sky background will easily be avoided by confining the measures to dense parts of the nebular image. However, consider a case in which there is no detectable background, this being due to the fact that the skylight lies $0{\cdot}5$ magnitude below the limit of detectability. From what has been said it will be clear that measures of even the dense parts of the image will be subject to serious error. For example, a part of the nebula which is two magnitudes above the limit of the plate, and which, therefore, shows as a region of quite considerable density, will, in this case, give a value for the true intensity which is in error by a tenth of a magnitude.

Combining these remarks with those on the subject of the influence of errors of determination of the sky background, we arrive at the conclusion that, for the determination of most of the isophotes, the exact determination of the sky background is a very important requirement. If the background is sufficiently dense to reduce the error of determination of m_0 to the level which applies to points on the straight line part of a characteristic curve, our discussion shows that the figures of merit for isophotes corresponding to quite small values of $m_0 - m$ will not be unduly low.

Hubble's rule.—In his studies of elliptical nebulae, Hubble (3) found that the surface brightness followed a law which, in terms of magnitudes, may be expressed as

$$m = m_e + 5 \log (r/a + 1),$$

r being the distance measured along a radius and a being a constant. A curious property of this rule which does not seem to have been noted is the following: If the curve representing this function is smudged by means of a Gaussian kernel so as to represent the effects of seeing, the resulting curve can also be represented to a high degree of accuracy by the same function with new values of the constants. It is not thought that this affects the present results. What significance, if any, is to be attached to this fact, it is hard to say, but it is curious that the brightness variation law should be one which is, practically, formally invariant under the seeing transformation.

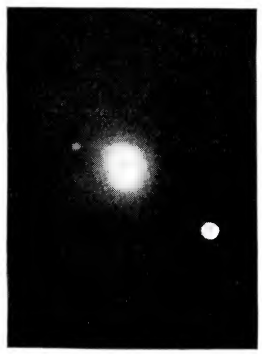
The results.—After taking the foregoing factors into account, we arrive at seven isophote maps illustrated in Figs. 2–8. The isophotes are drawn with an interval of 0·5 magnitude. The numerals indicate the figures of merit of the individual isophotes according to the system described above. The nebulae may be traced out still farther than they have been, but no great significance could be attached to these extensions. We shall probably not err on the side of over-confidence if we ascribe a probable error of 0·02 magnitude to a curve of merit unity, with errors inversely proportional to the merit for other isophotes. The error of location of an isophote of given merit on a map will, of course, vary with the determined brightness gradient at each point.

In the case of NGC 1553 the adopted background varied linearly across the plot by a total range of 0·2 magnitude between top and bottom of the figure (Fig. 8). Otherwise all backgrounds were taken as constant. The dotted lines represent "Hubble distributions" following the law cited above, which have been fitted to the observations. It will be seen that, in general, this law represents the observed distributions quite closely, except in the case of NGC 1553 which is anomalous. It is believed, following Hubble, that this law is, to a first approximation, a characteristic of elliptical nebulae, and it seems possible that it might be used as a criterion of classification. However, the fit is good only to a first approximation and, as Hubble found, there are points of deviation. For example, in the elongated nebula NGC 1380 changes of the ellipticity of successive isophotes are observable. Again, it has sometimes been stated that elliptical nebulae rarely show absorbing structures, but it will be seen from Plate 10 that a number of the objects discussed here (for example, NGC 1291) does show such structures. It will be further noted that the isophotal maps often show marked irregularities in the outer parts of the nebulae. Examples are the rift and tongue in the north following quadrant of NGC 1549, the southern patch of NGC 1380 and so on. It was thought at first that these merely represented errors of measurement at the limit of faintness which could be reached, but an examination of the material does suggest that these structures are represented

NGC 1553

NGC 1549

NGC 1344



NGC 1404

NGC 1291

NGC 1399

NGC 1380

N

p ↑ *f*

S

Scale : 1 *mm.* = 3″·7.

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on the plates and may have some basis in reality. Since they mainly occur on elongated nebulae it may be the case that these structures represent some sort of incipient spiral arms.

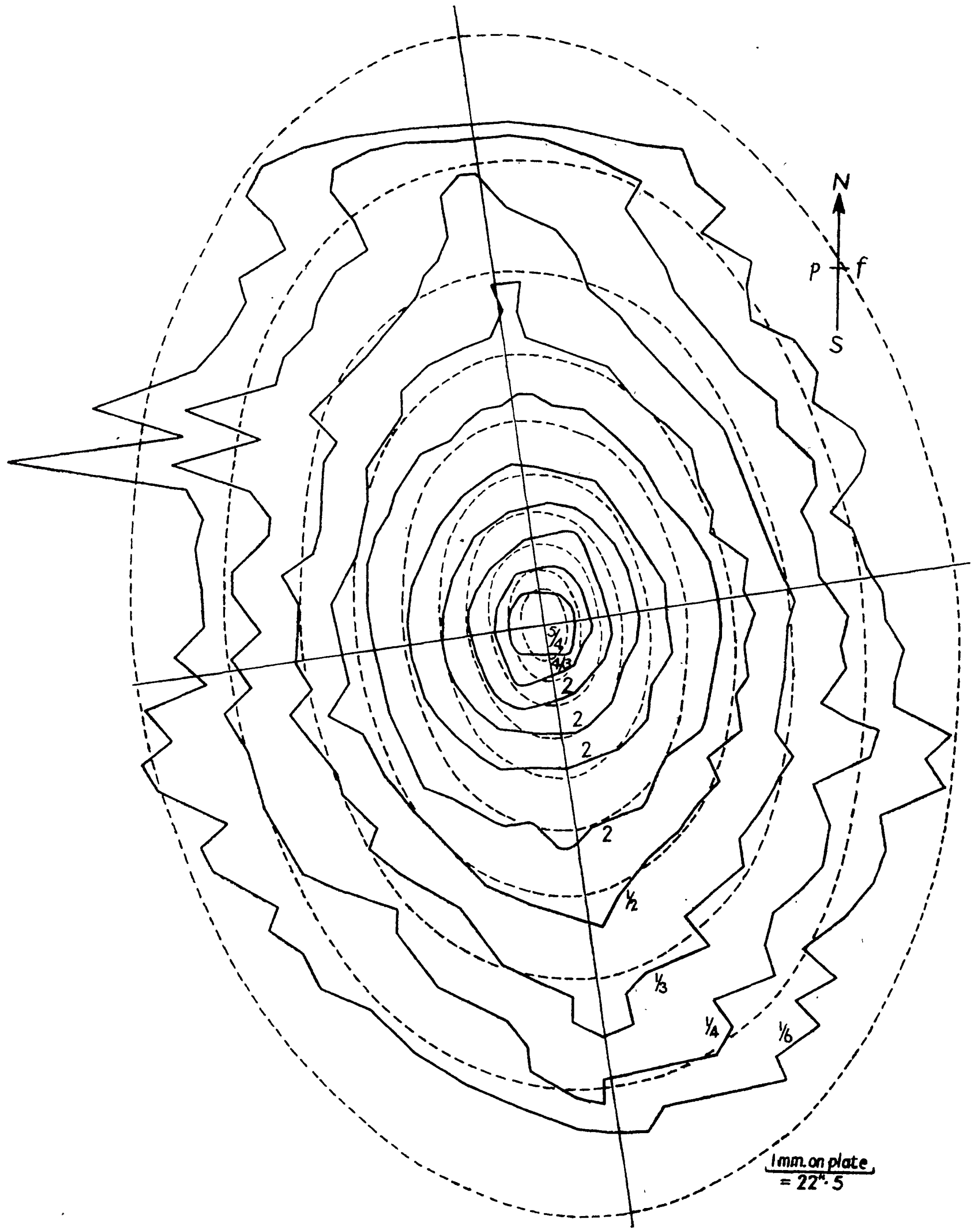


FIG. 2.—*NGC* 1291.

So far we have been on well-trodden ground and have done little more than provide some confirmation of Hubble's results. There is, however, a further point of interest which seems to be novel and which is best shown in the plot of NGC 1291. This is an elongated nebula of lenticular form showing axial extensions of many of the isophotes. If the central ones are re-drawn (Fig. 2 (*a*)) it will be seen that there is a steady rotation of the line of the major axes of successive isophotes, which one would be inclined to interpret as evidence of shear due to rotation. In the case of NGC 1291 there seems little doubt that this phenomenon is real. It shows up independently on two plates microphotometered at right angles to one another: it applies to the best determined isophotes; it is

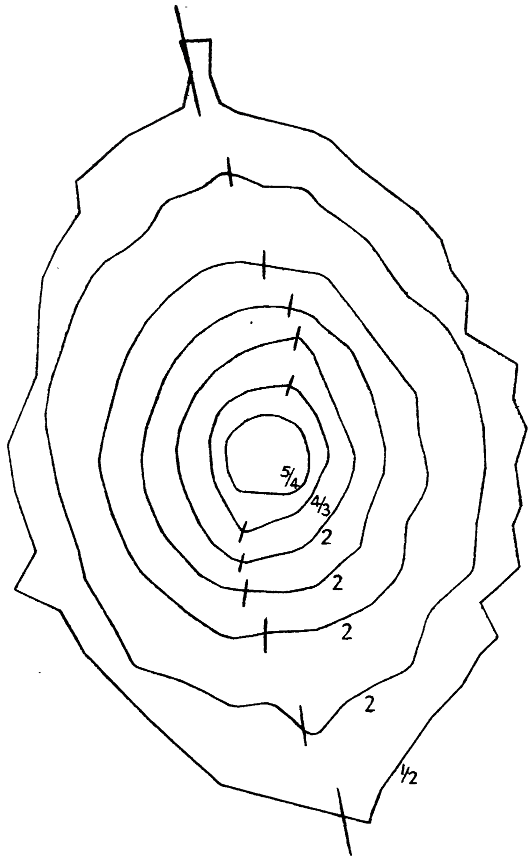


FIG. 2 (*a*).—*NGC* 1291.

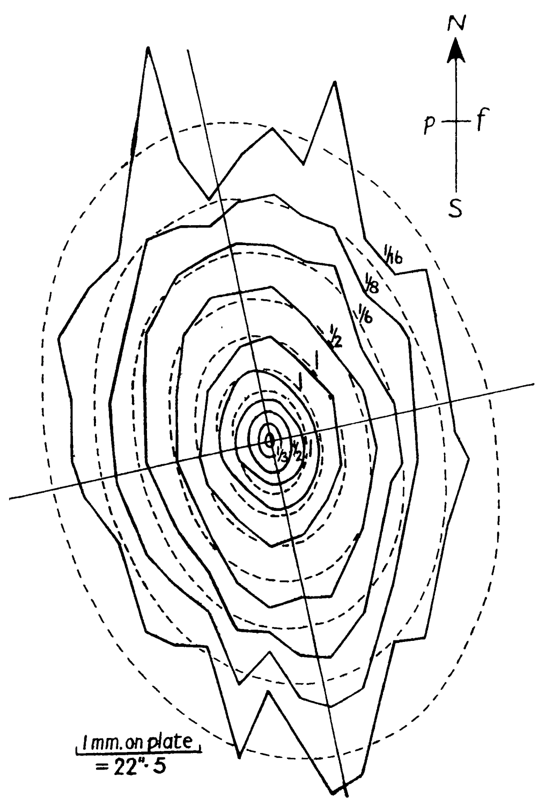


FIG. 3.—*NGC* 1344.

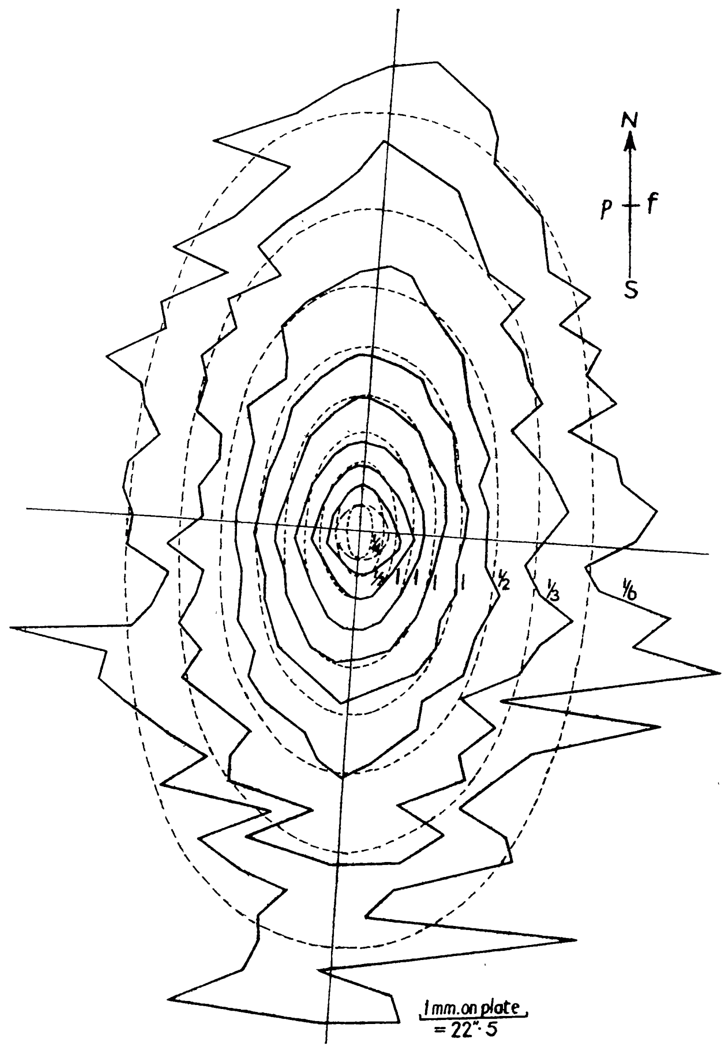


FIG. 4.—*NGC* 1380.

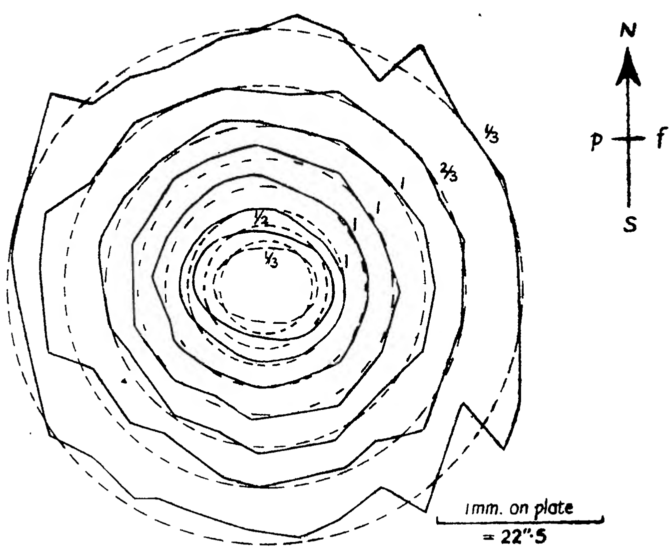


FIG. 5.—*NGC* 1399.

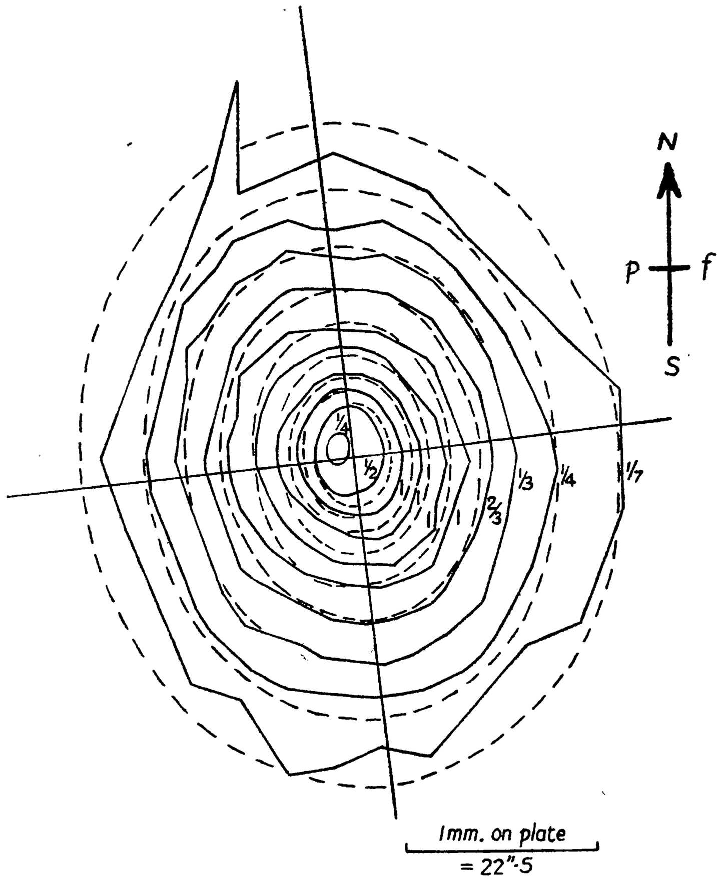
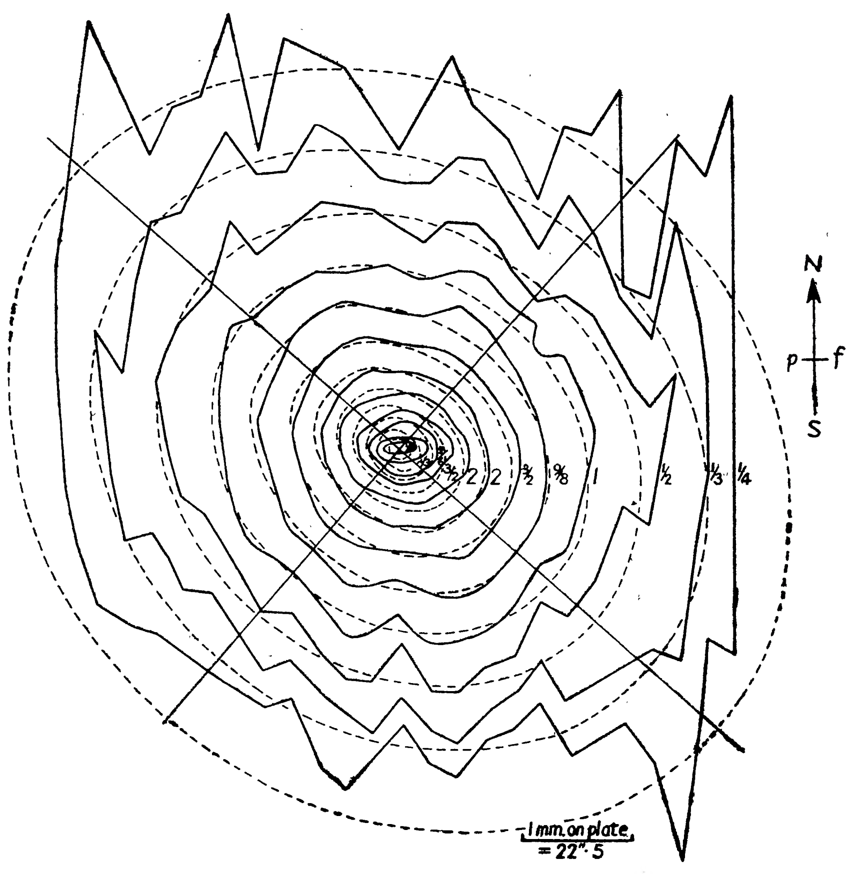


FIG. 6.—*NGC* 1404.



observed outside the range for which seeing, guiding and coma errors might be expected to be significant. I am inclined to believe that the similar phenomenon shown near the centre of NGC 1549 is also real, but here the effect is less well marked, and is only discernible with certainty for isophotes so small that they might be affected significantly by the errors mentioned above.

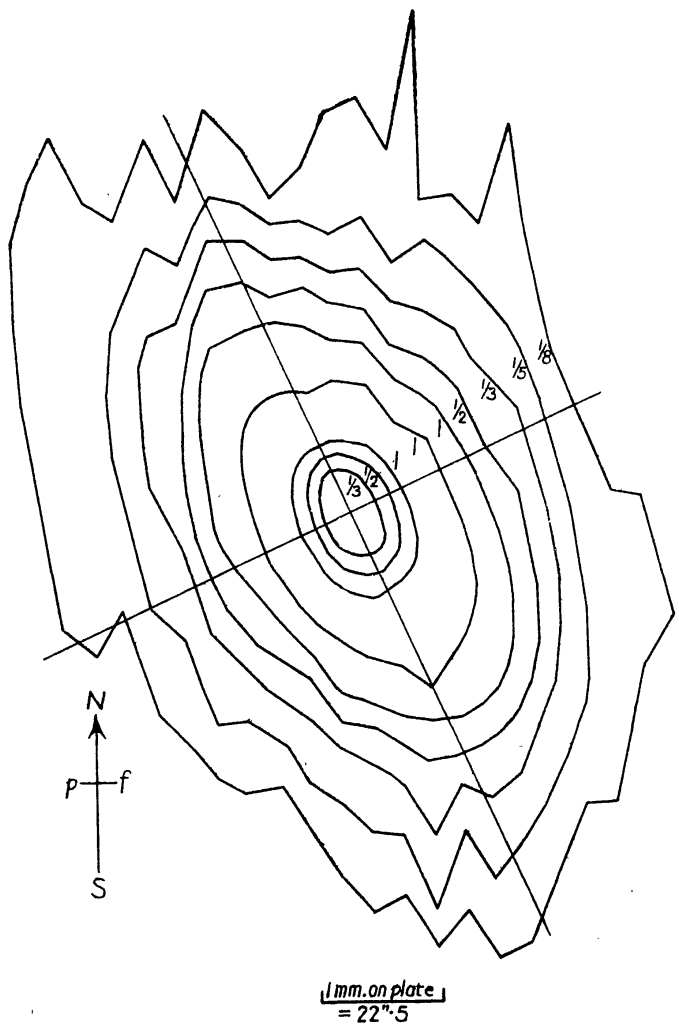


FIG. 8.—*NGC* 1553.

The case of NGC 1553 is anomalous. If one imagines a descent from the centre of an elliptical nebula, the brightness slope is, at first, steep, switching over to a gentler descent at an almost constant gradient. The curvature of the brightness–distance graph is always in the same sense. This is not true of NGC 1553 where, in the course of the descent, one reaches an almost level ledge. NGC 1553 resembles two elliptical nebulae seen one behind the other (it is not suggested that this is actually the case). The asymmetry about the central region of the faint "ledge", which is well shown on the isophote map, is real. While NGC 1553 seems hardly correctly classified as a spiral, as an elliptical nebula it is atypical.

The discussion of the observational results has been deliberately kept brief: the material available so far seems too limited to form the basis for generalizations about the structure of elliptical nebulae. The isophote maps are presented as they were determined, to provide theoretical workers with material for discussion. In the meantime observational material on the remaining bright southern elliptical nebulae is being accumulated as opportunity offers, and it is hoped to present this in due course. It may then become possible to discuss general questions, such as, for example, the applicability to all elliptical nebulae of the one-parameter law of surface brightness variation found by de Vaucouleurs (7).

I am much in the debt of Dr A. D. Thackeray for his criticism and comments on the present work throughout its progress. This paper has been much shortened at the suggestion of a referee.

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