STUDIES OF EXTRA-GALACTIC NEBULAE

PART I: DETERMINATION OF MAGNITUDES

By PHILIP C. KEENAN

ABSTRACT

A description is given of the method in use at the Yerkes Observatory for measuring the total magnitudes of nebulae by comparisons of extra-focal images. All comparisons are made directly with stars of the North Polar Sequence. After corrections for differential extinction and for size of image have been applied, the probable errors of the mean magnitudes are of the order of 0.06 mag. Irregularity in the shapes of the images is one of the most serious sources of error.

A catalogue of the brighter nebulae discovered on the survey plates is included.

1. INTRODUCTION

Photometry of the brighter external galaxies occupies an important place in the co-operative survey of these objects sponsored by the International Astronomical Union and organized under the leadership of Dr. Hubble of the Mount Wilson Observatory. The participating observatories have been left free to develop their own technique of observation; accordingly, we have worked out a provisional procedure for treating the zone assigned to the Yerkes Observatory, from $+50^\circ$ to the North Pole, on the basis of the equipment available. Several interesting photometric problems have arisen in the course of the work, and we feel that it may be of value to other workers in the field to discuss some of these points in advance of the publication of the survey catalogue, for which the observations will not be completed for several years. The important question of the influence of exposure time upon the measured magnitudes, and, in general, all points requiring a statistical treatment of the observed magnitudes, must be set aside until more material is available.

2. CHOICE OF METHOD

In this work we have been concerned primarily with the determination of integrated magnitudes, neglecting for the present the problem of surface brightness.

The observed magnitudes will tend to be influenced by irregularities in the shape of the galaxies and in their degree of condensation.

The effects may be expected to depend upon the type of the nebula, its size, and its brightness—the very quantities which will be required often as variables if any statistical use is to be made of the data. Thus it is clearly essential that the observations be arranged so as to make these systematic errors as small as possible. This may mean the abandonment of methods which lead to the most consistent results for individual objects or even for whole groups of homogeneous nebulae, but the most casual inspection of a few photographs is enough to show that the diversity in size and shape of the nebulae, and in the number of foreground stars, is so great as to make very low values for probable errors illusory in so far as comparisons between galaxies are concerned. It is desirable also to make supplementary investigations to detect the residual systematic errors which will necessarily be present to a greater extent than in stellar photometry.

In practice we wish to express nebular luminosities in the international system of magnitudes, so that the problem is to photograph a set of standard stars and a nebula in such a way that the images will be comparable. This can be done either by taking the images out of focus with a refractor or by trailing near-focus images with a moving-plate camera[1] so as to produce rectangular hatchings of any desired size. The latter device has the advantage of being adaptable to any type of telescope, but is a rather complicated instrument. With properly designed equipment it is possible to obtain nearly constant density across the images by either means. Since there is available at the Yerkes Observatory the Zeiss doublet of UV glass (aperture: 14.5 cm; focal length: 81 cm), giving images of excellent quality over a field of several degrees when the plate is taken inside the focus, we have decided to employ the extra-focal method for the present survey.

The size to be given the images and the method of measurement are the next points to be considered. With all minor differences of procedure disregarded, there are two possibilities:

a) Both nebula and stars are spread over an area several times wider than the maximum diameter of the nebula. Since all portions of the nebula contribute equally to each part of the image, except

[1] W. H. Christie, *Ap. J.*, **78**, 313, 1933.

near the edges, the surface brightness of the image is proportional to the total brightness of the source, and measurement is carried out with the diaphragm of the photometer smaller than the extra-focal disk.[2]

b) The distance from the focus for the nebular exposure is made only great enough to smooth out the irregularities in the shape of the nebula. The images will then be considerably smaller than those of method (*a*). The photometer opening is made slightly larger than the images, so that the total blackening of the plate by the nebula is measured and compared with the corresponding deflections for the comparison stars.

It appears to be generally recognized that method (*a*) is photometrically the more exact in that it more effectually smooths out the irregularities of the emulsion and the distortions of the optical image, which give rise to field corrections.

When an attempt is made to apply this method to nebulae, however, two serious difficulties are encountered. In the first place, the exposure times are considerably lengthened. Since the nature of the measurement requires a diameter at least double that of the focal image, the area will be increased by a factor of 4 as a minimum. Experience with method (*b*) suggests that its use will result in something like a twofold magnification of areas, and it may therefore be estimated conservatively that it will produce a given density with not more than half the exposure time required by method (*a*).

The second difficulty to hinder the employment of such large images is the presence of numerous foregound stars close to the nebulae. In order to see how frequently such stars intrude into the line of sight, ninety-four nebulae photographed with the 24-inch reflector were examined. The focal images of 31 per cent of these were influenced by stars, of which by far the greater part were undoubtedly foreground objects, and 16 per cent of the whole number had stars actually in front of the galaxies. In such cases, except when the stars are several magnitudes fainter than the nebula, it is practically necessary to measure stars and nebula together and then to subtract the intensity due to the stars as determined by galvanometer deflections for similar ones outside the nebula. It is clear that such correc-

[2] *Ibid.*

tions can only be approximated at best and will introduce considerable uncertainty into the results when the stars involved are bright. The number of wholly or partly superposed stars will increase more rapidly than the area of the images, so that the expected accuracy of measurement of large images will often be lost through the indefiniteness of the quantity measured.

For these several reasons it appears that method (*a*), superior though it is for compact isolated nebulae, will be applicable to a smaller range of objects, and will more frequently require the working-out of individual corrections, than will method (*b*), when account is taken of the great range of sizes and magnitudes to be covered by this survey. We have, therefore, chosen method (*b*) as our standard, but hope to employ the alternative procedure on a few selected objects as a check on the magnitude scale.

TABLE I

ΔF	Diameter
1.5 mm	0.31 mm
2.0	.40
2.5	.49
3.0	.58
3.5	0.69

3. OBSERVATIONS AND MEASUREMENTS

In accordance with the suggestion made by Hubble in his outline of the program for the survey, our scale of magnitudes of the nebulae is based upon exposures of uniform length. The exposure time adopted is one hour, which will give satisfactory extra-focal images with the UV camera for objects brighter than the fourteenth magnitude.

The average diameters of images of stars taken at different distances inside the focus of the UV camera are given in Table I. The data of the table apply to images dense enough to give deflections just above the toe of the calibration-curve.

In practice it is usually possible to obtain fairly uniform images of the galaxies, the values of ΔF ranging from zero, for a few diffuse nebulae, to 1.5 mm and more for nearly stellar objects. The comparison stars are then made to match the nebula by putting them out of focus by from 1.5 to 3.0 mm.

Because of the high northern declination of the zone assigned to the Yerkes Observatory, it has been found practicable to compare every nebula directly with the North Polar Sequence. The exposures are of equal length, preferably with each nebula plate taken between two calibration plates, but, since the exposures are of an hour's duration, a single calibration has to suffice in many cases. The long exposures make it necessary also to take the nebula and the pole on separate plates, not only because of the excessive density of the sky background when the exposures are superposed on a single plate, but also to avoid overlapping of the broadened images. In every case the plates to be compared are taken from the same box and are developed together in a tank, with continuous agitation of the rack in the developer, which is Eastman D-11.

In Plate III a pair of well-matched exposures are reproduced; the images shown are slightly smaller than the average.

Observers dealing with zones farther south will probably have to rely upon neighboring Selected Areas as standards, but these have the disadvantage of giving calibration-curves of unequal reliability, since some of the areas contain few stars in the magnitude range considered. At the Yerkes Observatory the zenith distance of the pole is $47^\circ.4$; hence the loss of light involved in taking the nebulae at approximately the same altitude as the Polar Sequence is less than 0.2 mag. Each plate is corrected for the remaining differential extinction, the amount of the correction averaging +0.06 mag. for the plates taken to date.

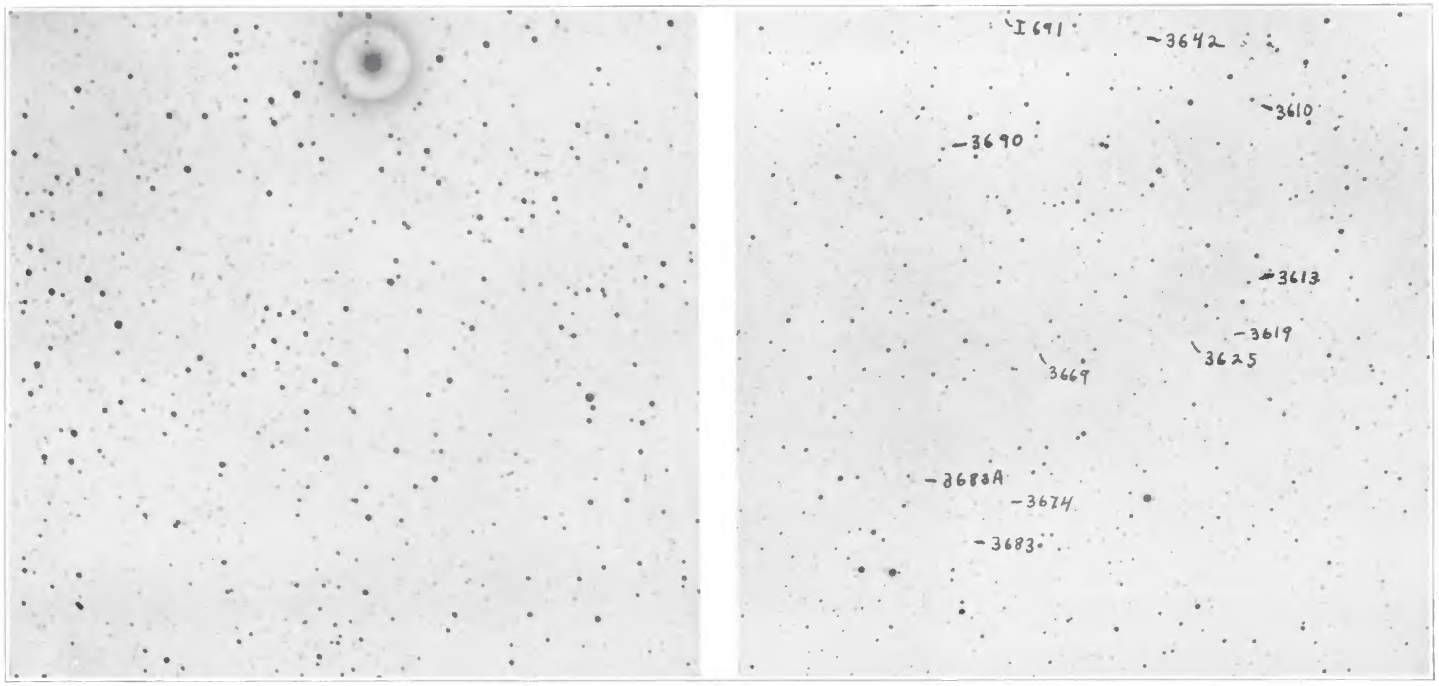
All photometric measurements on the plates have been carried out with the new thermoelectric photometer designed by Dr. F. E. Ross and constructed by Mr. Charles Ridell in the Yerkes shops. The design and operation of this instrument will be described in an article by Ross.[3]

In order to secure uniformly high sensitivity each series of plates is measured through a diaphragm passing a beam whose diameter, as focused on the emulsion of the plate, is just greater than the maximum diameter of the largest image to be measured. In the present arrangement all nebulae having image diameters not greater than about 1 mm ($4'$ on the UV plates) can be treated in this way.

[3] To be published in the *Astrophysical Journal.*

PLATE III

N



W

a *b*

ENLARGEMENT 2×. SCALE: 2′ = 1 MM

a) UV 2144. North Polar Sequence. Focal distance: −1.8 mm
b) UV 2143. R.A. 11^h22^m. Dec. +58°.0. Focal distance: −1.2 mm

The few larger nebulae on the program could be measured similarly by greatly reducing the magnification of the beam between the emulsion and the thermocouple, but since these objects are the ones suffering the greatest interference from foreground stars, it seemed best to deal with them on a different basis. Their total magnitudes are determined indirectly from their measured areas and from their surface brightnesses as derived from focal plates compared with large extra-focal images of the Polar Sequence. This procedure is admittedly inaccurate, but is adopted provisionally for want of a better one.

4. CONSISTENCY OF ATMOSPHERIC EXTINCTION

The direct comparison of photographs taken with the times of mid-exposure more than an hour apart requires observational justification, for these intervals are longer than those usually spanned by astronomical photometry. A critical test of the consistency of the results is made by comparing pairs of calibration plates. Such pairs allow an estimate of the maximum effect of the variation with time of the transparency of the sky, inasmuch as they are taken more than two hours apart, with a nebular exposure separating them.

In most cases the calibration plates preceding and following a photograph of a given field of nebulae are made at somewhat different focal settings in order to permit comparisons with several nebulae of varying size, particularly if the sequence of plates is continued by additional photographs on the same night. For this reason the number of plates suitable for tests of the uniformity of extinction, for which purpose the images on a pair must be as nearly identical as possible, is small. However, we have available twelve well-matched pairs taken on transparent nights, and these are sufficient to give a good idea of the reliability of the calibration-curves.

Four of these pairs of curves are plotted in Figure 1. These were selected at random and represent normal results, except that the differences between the curves for UV 2142 and UV 2144 are the greatest found on any pair yet taken on a very clear night. It is significant that the transparency on that particular night was estimated by the observer as diminishing during the exposures from 3+ to 3 on our scale. The average deviation of each curve of a pair from the mean of the two, from all twenty-four plates used, amounted to 0.06 mag. for very dense images, 0.03 mag. at intermediate densities, and 0.02 mag. for images in the toe of the curve. The larger value found for the bright stars is due in part to slight changes in the focus, which was set separately for each plate.

The agreement is about as good as could be hoped for even if the exposures were of only a few minutes' duration. This result may seem a bit surprising at first, but is probably to be explained by the

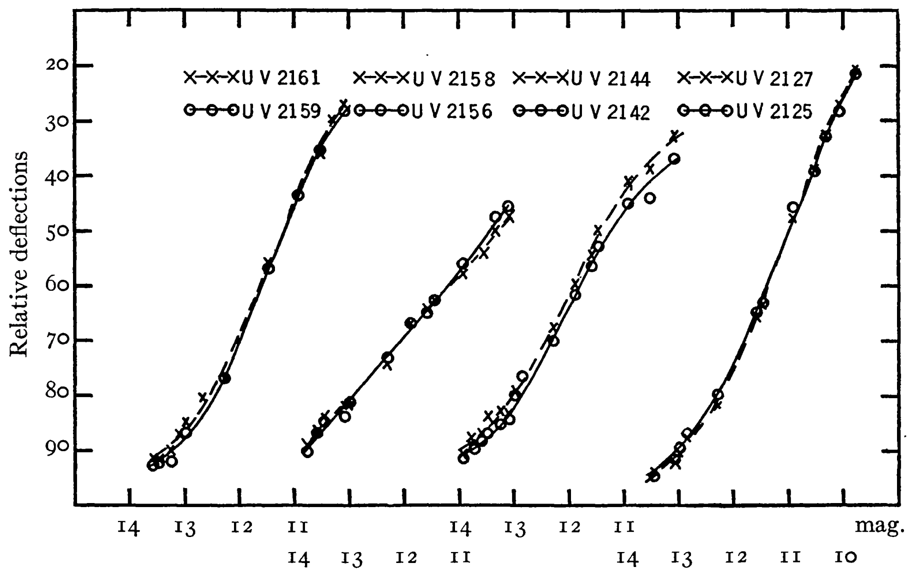


FIG. 1.—Pairs of calibration-curves. Ordinates are ratios of deflections: star to background fog.

fact that the atmosphere is frequently subject to short-period fluctuations in transparency, which are partly smoothed out by the longer exposures.[4] In any case it may be concluded that successive one-hour exposures made on good nights can safely be compared as long as the observer does not detect changes in the transparency, as judged by the visibility of faint stars near the pole.

5. CORRECTION FOR SIZE OF IMAGE

Since the field corrections of the UV camera have been found to be caused chiefly by the change in the areas of the images in going from the center to the edge of the field, a series of plates of the Polar

[4] I am indebted to Dr. Elvey for a discussion of this point.

Sequence at varying focal settings was taken in order to determine the relations between size of image and measured magnitude.

The resulting corrections for a diaphragm having an effective aperture of 0.9 mm are shown in Figure 2, where each curve is the

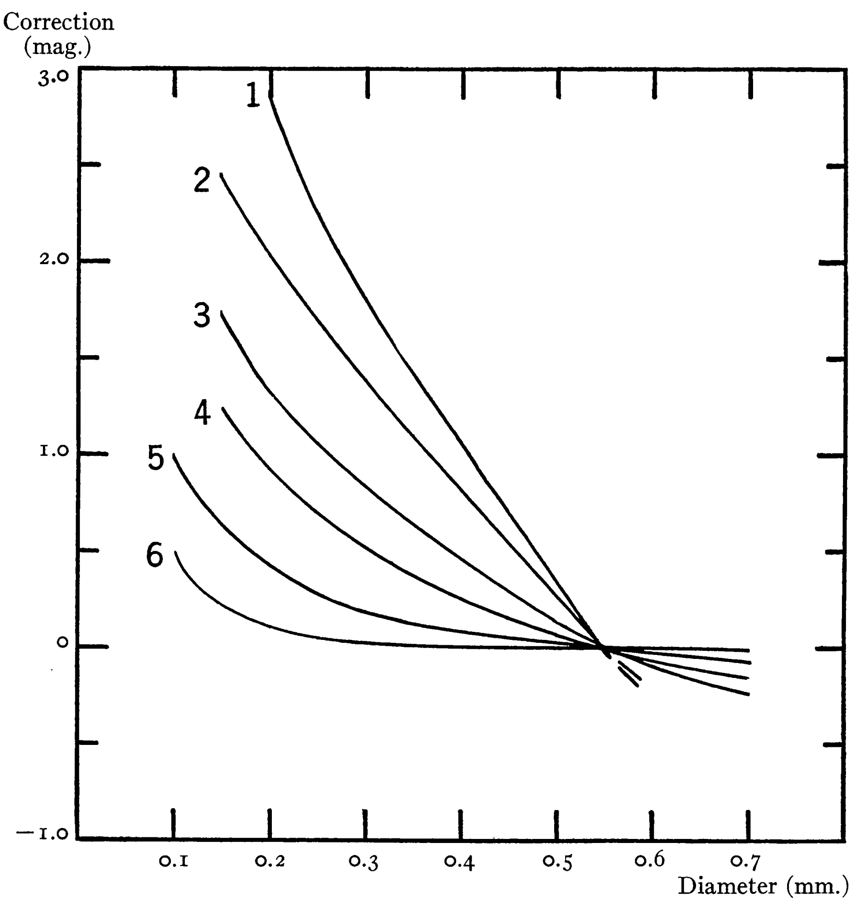


FIG. 2.—Variations in measured magnitude with diameter of image. The numbers refer to position on the calibration-curves, expressed as percentages of the total height of the curve, lower numbers corresponding to higher densities, as follows: *1*, 10–20 per cent; *2*, 20–40 per cent; *3*, 40–55 per cent; *4*, 55–70 per cent; *5*, 70–85 per cent; *6*, 85–100 per cent.

average for images spread over a range of about seven-tenths of a magnitude in brightness. The irregularities in the progression of the curves reflect the large scatter found in the individual points from the fourteen calibration-curves from three plates used in forming the means. The average deviation from the mean of the separate observations going into the lower four curves is 0.09 mag. Curves 1 and 2 depend upon only a few points, but are seldom used. The diagram relates the corrections arbitrarily to a value of zero for an image diameter of 0.55 mm, which happens to occur frequently, but the curves could equally well be drawn to cross the zero line at any other diameter.

The curves behave as might be expected from a consideration of the structure of the images. For faint stars the density of images of all sizes is so low that enough light is transmitted to affect the photometer readings; consequently, the loss in density with increasing size largely compensates for the greater area of absorption, and the corrections are small. On the other hand, the images of very bright stars are effectively opaque in all sizes and should produce galvanometer deflections which are proportional to the area of clear plate around the star but are relatively insensitive to the magnitude of the star. The large and uncertain corrections for dense images are thus explained.

If Figures 1 and 2 are compared it is seen that nebulae falling just above the toe of the calibration-curve give the most satisfactory determinations of magnitude, even when they differ appreciably in dimension from the comparison stars.

For all magnitudes of nebulae measured up to this time and given a weight high enough to be regarded as satisfactory, the average correction applied due to difference in size of image is 0.05 mag., a mean of 76 values taken without regard to sign.

6. EFFECT OF SHAPE OF IMAGE

It is important and at the same time difficult to obtain direct experimental evidence of the extent to which the measures are affected by irregularities in the density distribution of the images.

Consider, first, images which are approximately circular but which differ in their radial distribution of density. The imperfections in the images formed by the 10-inch Bruce lens provide a convenient way of bringing about this condition. The lens is overcorrected for spherical aberration, so that stars taken inside the focus appear as small intense nuclei superposed upon faint disks several times as broad. On the other hand, the images formed outside the focal plane are relatively faint near their centers but are sharply bounded by bright rings. A comparison of the same stars photographed on opposite sides of the focus will thus permit a rough estimate of the maximum differences to be expected if centrally concentrated spheroidal nebulae and open spirals were measured together on focal plates.

From a number of exposures made in this way with the Bruce telescope the systematic differences are found to be not only large but also inconsistent from plate to plate. The variations in the results are probably due in part to threshold effects connecting the fainter portions of the images with the density of the fog background. However, the general course of the measures can be seen from the typical set of calibration-curves given in Figure 3, which offers further evidence of the necessity of taking the brighter nebulae far enough out of focus to insure approximate uniformity of density.

On the two plates taken outside the focus, at -1.2 and -2.0 mm, the images have a diameter of 0.27 and 0.36 mm, respectively, throughout the greater part of the range of magnitudes covered. Only the nuclei of the images of the fainter stars appear on the exposure taken 1.4 mm inside the focus and, therefore, the toe of its curve lies a little below the corresponding portions of the other two. Passing to the bright stars, we find that the broad disk due to the axial rays has become so strong that the images have an effective diameter of about 0.65 mm, which is sufficient to raise their calibration-curve far above the others. Between the two ends there is a transition stage in which the background image is just reaching threshold density, and here the curves cross, though in this region the diameters of the images characterized by nuclei are so vague as to be practically unmeasurable.

Some information concerning the effect of comparing round and elongated images with each other has been secured from a special series of plates of the Polar Sequence, taken with the UV camera. On these the round disks had an average diameter of 0.5 mm, while the oblong images were obtained by moving the plate-holder by a hand screw back and forth over a distance of about 0.6 mm, the original diameter of the images being 0.3 mm. The trailed images produced in this way had a ratio of axes of a little less than 3 to 1. The areas of the two types of images were almost exactly equal on the average, and corrections for the small individual differences were applied in the usual manner.

The calibration-curves for the seven sets of elongated images and six sets of round ones are practically identical in shape. The latter have a slightly greater slope; hence, the oblong images are measured as too faint by 0.20 mag. for dense images, 0.08 mag. for images of

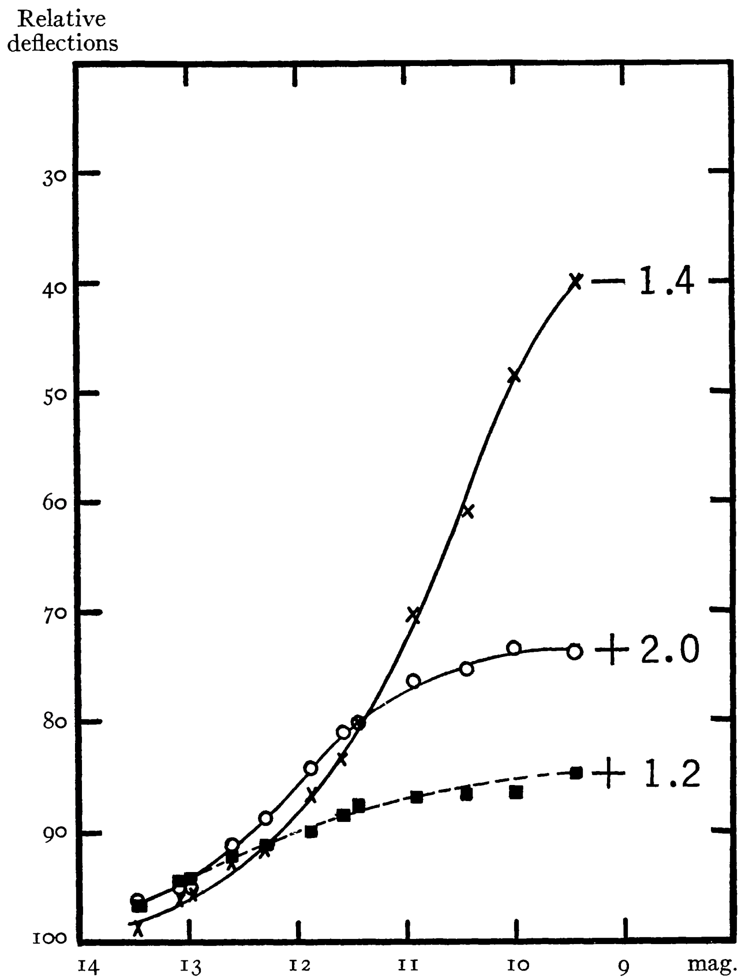


FIG. 3.—Bruce calibration-curves. Numbers at the ends of the curves refer to distances from the focus, in millimeters.

moderate strength, and 0.03 mag. for those near the toe of the curves. For densities corresponding to those obtained with most of the nebulae on our program the mean difference is about 0.06 mag., but the amount is too small to be well determined, the average deviations of individual values from the mean being of the same order.

These results indicate that as long as the densities of the images are fairly uniform their shapes are not very critical factors. There will probably be systematic differences of the indicated order between narrow spindles and nearly round spirals, but the extensive investigation necessary to determine accurate corrections for various degrees of elongation appears to be scarcely feasible at present, particularly in view of the larger errors due to other sources.

7. PRECISION OF THE MEASURED MAGNITUDES

A final evaluation of the accuracy of the integrated magnitudes must await the completion of the program, but we can estimate the errors fairly closely from the data for twelve nebulae for each of which at least four independent measures of satisfactory weight are available. These objects are listed in order of their NGC numbers in Table II. The second column gives the weighted mean photographic magnitude, followed by the probable error of a single observation in the third. Since it is intended that the final magnitude of every nebula will be based upon at least two observations of adequate weight, the probable error of the mean magnitudes may be expected to be in the neighborhood of 0.06 mag.

TABLE II

ACCURACY OF NEBULAR MAGNITUDES

NGC	M_{pg}	r
2268	$12^{m}.36$	$0^{m}.08$
2276	12.08	.07
2300	12.25	.04
2655	11.00	.09
2748	12.44	.08
3683	12.90	.15
3982	12.26	.02
5874	13.33	.07
5875	13.27	.15
5908	13.02	.09
6359	13.59	.10
6381	13.38	0.05

Before it will be possible to tell how successfully we have reduced systematic errors, especially those discussed in the last section, a larger accumulation of material must be at hand, permitting comparisons of the results obtained with different instruments and by different methods with the same telescope.

8. NEW NEBULAE

A number of previously uncatalogued nebulae of the fourteenth magnitude or brighter appear on the plates. For the benefit of other observers Table III gives approximate positions (epoch 1950) of such

TABLE III

NEBULAE DISCOVERED ON SURVEY PLATES

Nebula	R.A.	Decl.	Remarks
1530A......	$4^h38^m.2$	$+75°37'$	$12^m.88$
1573A......	4 42.7	73 26	$14^m.0$
2146A......	6 16.0	78 35	$13^m.66$; $3'.0\times1'.7$ in P.A. 25°; irregular
2273A......	6 36 :	60 07	
2273B......	6 42.2	60 24	$2'.2\times1'.9$ in P.A. 38°; SB:
2326A......	7 04.9	50 44	14^m; $1'.2\times0'.9$ in P.A. 14°; E_3:
2336A......	7 50 :	78 19 :	
2523A......	7 58.4	74 14	
2523B......	8 07.1	73 44	$2'.3\times0'.5$ in P.A. 92°; Sc
2523C......	8 12.0	73 30	$0'.9\times0'.6$ in P.A. 74°; E_4:
2550A......	8 23.6	74 04	
2742A......	9 06 :	62 22 :	$13^m.7$
2959A......	9 41.2	68 51	$0'.8\times0'.25$ in P.A. 144°; Sb
3683A......	11 27 :	57 23 :	$13^m.11$
3759A......	11 34.2	55 26	$13^m.9$; $1'.3\times1'.2$; E_0:
3795B......	11 36 :	59 03 :	$13^m.7$
3795A......	11 37 :	58 23 :	
3846A......	11 42 :	55 18 :	$13^m.5$
3835A......	11 44.7	60 36 :	
3917A......	11 48.8	52 15	$13^m.9$
4085A......	11 58 :	51 12 :	$11^m.6$
4125A......	12 02.2	64 42	$13^m.8$; $1'.2\times0'.3$ in P.A. 132°; Sa:
4108A......	12 03.3	67 32	$1'.2\times0'.4$ in P.A. 9°; Sb
4108B......	12 04.8	67 30	$0'.9\times0'.6$ in P.A. 0°; E_3:
4250A......	12 15 :	71 09 :	$13^m.5$
5216A......	13 33.0	62 16	14^m
5875A......	15 07 :	52 29 :	$0'.6\times0'.6$; Sa:
5866B......	15 10.9	55 58	$2'.2\times1'.7$; Sc
5976A......	15 35.1	59 43	
6246A......	16 48 :	55 47 :	$13^m.5$
6493A......	17 49.3	61 30	$1'.6\times0'.7$ in P.A. 39°; Sb
6654A......	18^h41^m	$+73°30'$:	$13^m.2$. $2'.6\times0'.7$ in P.A. 62°; Sc

objects noted to date. Temporarily each nebula is designated by the number of the nearest NGC object on the plate, followed by a capital letter. Dimensions and provisional magnitudes are included when available.

YERKES OBSERVATORY
March 1935