NO. 21. SURFACE PHOTOMETRY OF EXTENDED IMAGES*

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1. *Introduction*

THE class of objects whose focal images extend over an area of plate appreciably greater than that of a point source includes planetary nebulae, galaxies, and bright interstellar matter. Information about the total integrated brightness and color, the shape and distribution of relative or absolute intensities over the surface, and the total extent of the object, both in integrated light and for selected spectral regions, is of importance.

2. *Dimensions*

The extent of an image of a planetary nebula or galaxy may be estimated by tracing photometrically across the image. (When the trace is properly calibrated, the procedure can also yield a measure of the brightness per unit area at any point and will be referred to again below.) Holmberg (1946) measured the apparent diameters and orientation in space of a number of elliptical galaxies. For calibration of the apparent axis ratios (orientation measures) artificial nebular images, produced by rotating sectors of light of different shapes, were used.

The dimensions and shape of the Andromeda Nebula have been investigated photographically by Shapley (1934), Redman (1936), Redman and Shirley (1937), Williams and Hiltner (1941), and others. Measurement of the optical density of the plate may be used to assess the dimensions of an object to various limiting surface brightnesses; a convenient unit for surface brightness is magnitudes/sec^2.

The various definitions and measures of galaxy diameters have been discussed by de Vaucouleurs (1959*a, b*).

3. *Apparent Magnitudes*

A very accurate program of measurement of total photographic and photovisual magnitudes of galaxies has been carried out by Holmberg (1950, 1958). In 1950 he published measures for 39 nearby galaxies; later he gave integrated magnitudes and colors for 300 others (Holmberg, 1958). The method used was the following.

An in-focus image of a galaxy was obtained on one-half of the plate, out-of-focus images of stars of the North Polar Sequence being registered on the other. A series of photometric tracings were made of successive sections of the galaxy, the Polar Sequence stars providing the standard intensities for calibration, and the integrated magnitudes were obtained by summation. The method is slow and tedious, but apart from the slight ambiguity of the N.P.S. standards, reliable. The accuracy of the final photographic and photovisual magnitudes was high, the mean error being $\pm 0^{m}.04$. Lyngå (1959) used a similar method to obtain the integrated magnitude of the Andromeda Nebula, the (photoelectric) standards being selected from the Pleiades. Efimov (1959) obtained integrated magnitudes of NGC 7293 at 6550A, using the Pleiades as standards, and derived a measure of the

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electron density and a rather uncertain estimate of the mass of the nebula.

Bigay (1951*a*) used Fabry photometry (see Stock and Williams, 1962) to obtain photographic magnitudes of 175 bright galaxies. He has also made a critical survey and comparison of methods used up to 1951 for measuring integrated magnitudes of galaxies (Bigay, 1951*b*). A previous similar survey for surface brightness distribution by photographic methods was made by de Vaucouleurs (1948).

The schraffier method has also been used for estimating magnitudes of extended objects. On a schraffier-kassette plate, square images of uniform density are obtained by guiding the telescope in a regular pattern by a mechanical device called a jiggle-camera, the plate being slightly out of focus (Humason, Mayall, and Sandage, 1956; Zwicky, Herzog, and Wild, 1961). The schraffier images are then calibrated by comparison with similar images of suitable standards; measurement of the density of the images gives the magnitudes of the objects. Loss of limiting measurable magnitude depends on the size of the schraffier image used (1, 2, or 4 mm, Humason *et al.*, 1956; 1′ on out-of-focus Schmidt plates, Zwicky *et al.*, 1961).

In direct photometry systematic errors in the measurement of the apparent magnitude or of the diameter may be caused by neglect of the outer regions of low luminosity in an extended object. Zwicky *et al.* (1961) note that because the diameters of the larger galaxies measured may be comparable in the schraffier method with the size of the schraffier squares, results may be distorted, and corrections should be applied. In the Fabry method, the use of too small a field diaphragm may cause systematic errors. De Vaucouleurs (1956*a*, *b*, 1957, 1959*a*) reviews the causes leading to discrepancies between the major catalogues of magnitudes of galaxies. Humason *et al.* (1956) also give a useful discussion of possible systematic errors of the schraffier method.

A method of determining magnitudes of galaxies by out-of-focus photometry is described by Abell (1958, p. 215-217). The method does not aim at very high precision, but a useful discussion of sources of error is given, with particular attention to the zero point.

4. *Isophotometry*

Contours of equal surface brightness, called *isophotes*, can give useful information about the distribution of brightness within an extended object, and about the structure. Evans (1949, 1950, 1951, 1952) obtained crude isophotes of a number of planetary and elliptical nebulae in several colors from conventional microphotometer tracings. He plotted the points of constant density for several cross-sections of the nebular image, calibration being made by comparison with a sequence of spots of known density (see also Redman, 1936; Redman and Shirley, 1937; and others). A similar technique has been applied with success by Sérsic (1957, 1958*a*, *b*, *c*, *d*, 1959). Use of an iris diaphragm photometer to plot contours of constant density has been described by de Vaucouleurs (1956*b*). Rasmadse, Irochnikov, and Kotok (1959) obtained isophotes for [OII] at 3727A for the planetary nebula NGC 6853, using photographs obtained with a 70-cm meniscus telescope. A detailed treatment of the techniques involved in the production of isophotes by equidensitometry is given by Lau and Krug (1957).

A photographic method of obtaining isophotes suitable for nebulae of intricate structure has been described by H. M. Johnson (1960). Plates of the Southern Milky Way were enlarged directly onto Eastman Kodalith film of very high contrast, and the resulting boundaries between black and white areas were calibrated from tube sensitometer spots (a number of which, depending on the exposure time, disappeared on the positives). The boundaries, or isophotes, were then mapped onto a grid representing the star field. It should be noted that in this method care is needed in relating the independently obtained contours to each other and to the field. A similar method was previously described and applied to M42 by von Hoff (1937).

Williams and Hiltner (1940, 1941) describe a modification of a densitometer, built at the University of Michigan Observatory at Ann Arbor, which enables direct continuous traces of isophotal contours for a series of density steps to be made by a null method. This machine made use of many features embodied in the General Electric recording spectrophotometer (Hardy, 1938) with ingenious modifications of the original design intended to adapt it for the measurement of photographic plates.

A plate of suitable density of the object for which isophotal contours were to be obtained was placed on a carriage which could be driven in a given direction X while movement of the plate was also possible in a direction Y at right angles. A beam of light passed through the plate, while one of several calibration spots was centered in a comparison beam. Means were provided for directing the two analyzing light beams from the two mechanically separate microdensitometers alternately onto the common photocell. The position of the plate was adjusted automatically in direction Y until the light beams compensated, i.e., *hunting* by the instrument continued until a point on the plate was found by this adjustment whose density was equal to that of the comparison spot (the indicated difference in the signals from the photocell was reduced to zero within the limits of accuracy of the machine). As the motion in direction X proceeded, a curve of constant density on the plate was traced photographically, the final photograph being one of a family of such traces corresponding to a number of different densities. It should be noted that for the recording of isophotes for a planetary or elliptical nebula the carriage was run twice in direction X with a small displacement of the plate at right angles to X, the resulting traces forming two parts of the same closed contour. A disadvantage of this type of photometer is that for areas involving a large number of density peaks, as in some bright nebulae, the operation of the instrument becomes complicated, needing careful monitoring to insure the inclusion of all proper details.

Dennison (1954) and Miss Hazen (1957) obtained important data on the luminosity distribution in a number of galaxies from isophotometry using the Williams-Hiltner instrument.

A later version of the Michigan isophotometer has been described by Mohler and Pierce (1957), and further modifications have been made in the instrument now (January 1962) in use. In 1960 Dr. G. de Vaucouleurs used the instrument for isophotometry of 50 southern galaxies, and this work with a description of the method used will be published shortly.

Dr. Orren Mohler has kindly provided the following data:

> "A series of modifications in the original instrument was begun some ten years later[1] in order to adapt the microdensitometer more specifically to its use as an isophotometer. No change in the fundamental principle was necessary, and it was possible to improve enormously the sensitivity and stability. A discrimination between density differences of 0.003, and a stability such that no changes were necessary over a period of years were finally achieved.
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> "The Williams-Hiltner machine produces a curve connecting all points of constant selected density in the photographic image being investigated. An isophotometer may also be constructed that will scan a complete area of photographic plate according to a pre-selected routine (H. W. Babcock, 1950, *Pub. A.S.P., 62,* 18; N. N. Michelson, 1953, *Pub. Pulkovo Obs., 19,* No. 4, p. 69; O. C. Mohler and A. K. Pierce, 1957, *Ap. J., 125,* No. 1, p. 285). Two machines of this type have been constructed at the McMath-Hulbert Observatory of the University of Michigan. In the Michigan machines an analyzing light beam moves the full length of the plate (the X-direction), then is displaced a small step in the perpendicular direction (the Y-direction), after which it again traverses the X-direction on the plate in a sense opposite to the preceding trace. This procedure is followed until the entire area of the plate has been covered by the analyzing beam. A record is made on a paper tape by an inking pen whenever the intensity of the light beam transmitted through the photographic plate to the photoelectric cell reaches any one of a number of pre-selected levels. The pre-selected levels of intensity correspond to definite photographic densities.
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> "Early in 1958 a second model of an isophotometer with an X-Y scan was completed at the McMath-Hulbert Observatory. The second X-Y scanning isophotometer incorporated many improvements indicated by experience with the earlier versions. The later instrument produces isophotal contours at more than four times the speed with approximately twice the precision of the first X-Y machine. Neither of the X-Y isophotometers is as precise as the Williams-Hiltner instrument. It should be mentioned, however, that the X-Y machine will run unattended for days at a time when this is necessary for plotting isophotes covering large areas of a photograph.
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> "All isophotometers that record data only for certain pre-selected densities of the photographic image under study omit recording of the density at the unselected values. It is generally necessary to make more than one isophotal tracing of a plate with such instruments so that the trace of the region scanned on a first trial will be supplemented by a record filling in the gaps.
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> "Developments now under way at the McMath-Hulbert Observatory are directed toward the elimination of this defect. It is proposed that the X and Y positions of the scanning motions of a light beam and the intensity of the

[1] i.e., about 1950.

(*a*) (*c*)

(*b*) (*d*)

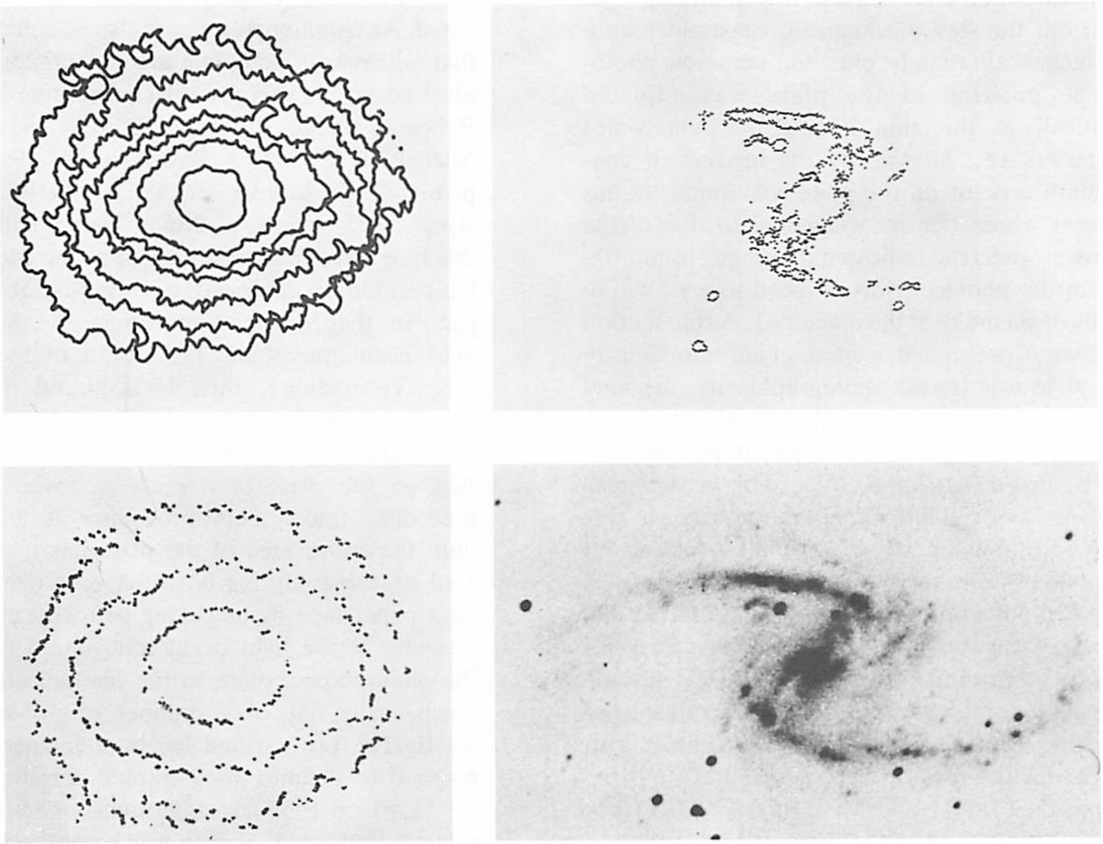

Fig. 1. Sample tracings by Griboval isophotometer (University of Texas). *Left:* Isophotes of type S0 galaxy NGC 1291 illustrating mode of operation as isophote follower with (*a*) continuous or (*b*) discontinuous recording; upper trace shows plate noise plus effects of "hunting"; lower trace shows effect of plate noise (granulation) only. *Right:* Isophotes (*c*) of barred spiral NGC 1365 (*d*) illustrating operation as plate scanner. (Photographs by courtesy of Dr. G. de Vaucouleurs.)

analyzing beam be recorded directly in a digital form. Results from a machine of this kind can be mechanically displayed in the form of tables containing the *X* and *Y* coordinates of each element of area on the plate and the photographic density within the area. The same data can be used to produce microdensitometric tracings in either the *X* or *Y* directions. A microdensitometric tracing may also be produced for any combination of the scanning coordinates; or, for the production of isophotal contours. The preliminary developments so far carried out indicate that a digital analysis of an astronomical image of ordinary degree of complication, and the tabulation of the data will require a considerable period of time. However, the presentation will be complete and in principle it is possible to record all significant photographic changes of density in any given image. The process can be speeded up by the investigator at the cost of sacrificing some degree of completeness in the results. Indications are that a machine of the type contemplated here will be significantly slower than either the original Williams-Hiltner machine, or the McMath-Hulbert *X-Y* recorders in the production of isophotal curves to equivalent degrees of precision. It is an unfortunate fact that so far none of the recent models of isophotometers has equaled the Williams-Hiltner machine in precision."

Another type of isophotometer, based on a modification of a conventional microphotometer, has been developed by Koelbloed at the Sterrenkundig Institut in Amsterdam. This is similar to the Pierce-Mohler instrument discussed above. Dr. H. W. Babcock (1950) designed an instrument, which was used by Dr. W. Baade to obtain uncalibrated isophotes of some planetary nebulae.

A new isophotometer designed by P. Griboval was placed in operation at the University of Texas in 1961 (de Vaucouleurs, private communication). This is a two-beam null AC photometer with two possible modes of operation. These are contour following and scanning in which points of exact balance between the measuring and comparison beams are recorded. Adjustment of a photometric wedge on the comparison beam permits selection of the isophote required. Direct inscription or photographic recording of the isophotes can be made, and the recording can be continuous or discontinuous. Figure 1 shows examples of isophotes recorded with the Griboval instrument for the galaxies NGC 1291 (type S0) and NGC 1365 (barred spiral).

REFERENCES

Abell, G. O. 1958, *Ap. J. Suppl.*, Vol. *3*, No. 31.
Babcock, H. W. 1950, *Pub. A. S. P.*, *62*, 18.
Becker, W. 1938, *Zs. f. Ap.*, *15*, 225.
————. 1942, *A. N.*, *272*, 179.
————. 1948, *Ap. J.*, *107*, 278.
————. 1950, *Sterne und Sternsysteme* (2d ed.; Dresden and Leipzig: Steinkopff).
Bigay, J. H. 1951*a*, *C. R.*, *232*, 312 (*Pub. Obs. Haute-Provence*, *2*, No. 15).
————. 1951*b*, *J. des Observateurs*, *34*, 89.
Dennison, E. W. 1954, *A. J.*, *59*, 320, and University of Michigan thesis (unpublished).
Dimitroff, G. Z. 1938, *Harvard Circ.*, No. 430.
Efimov, Y. S. 1959, *A. J. (U.S.S.R.)*, *36*, 457.
Evans, D. S. 1949, *M. N.*, *109*, 94.
————. 1950, *ibid.*, *110*, 37.
————. 1951, *ibid.*, *111*, 526.
————. 1952, *ibid.*, *112*, 606.
Greaves, W. M. H. 1952, *Trans. I. A. U.*, *8*, 355.
Hardy, A. C. 1938, *J. Opt. Soc. America*, *28*, 360.
Hazen, M. L. 1957, University of Michigan thesis (unpublished).
Hoff, H. von 1937, *Zs. f. Ap.*, *14*, 104.
Holmberg, E. 1946, *Lund Medd.*, *II*, No. 117.
————. 1950, *ibid.*, No. 128.
————. 1958, *ibid.*, No. 136.
Hubble, E. 1930, *Ap. J.*, *71*, 231.
Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, *A. J.*, *61*, 145.
Johnson, H. M. 1960, *Mem. Mt. Stromlo Obs.*, Vol. *3*, No. 15.
Lau, E. and Krug, W. 1957, *Die Äquidensitometrie* (Berlin: Akademie Verlag).
Liller, M. H. 1960, *Ap. J.*, *132*, 306.
Lyngå, G. 1959, *Lund Medd.*, *II*, No. 137.
Michelson, N. N. 1953, *Pub. Pulkovo Obs.*, Vol. *19*, No. 4, p. 69.
Mohler, O. C. and Pierce, A. K. 1957, *Ap. J.*, *125*, No. 1, p. 285.
Oort, J. H. 1940, *Ap. J.*, *91*, 273.
Patterson, F. S. 1940, *Harvard Bull.*, No. 914, p. 9.
Rasmadse, N. A., Irochnikov, R. S., and Kotok, E. V. 1959, *Bull. Obs. Abastumani*, No. 24, p. 31.
Redman, R. O. 1936, *M. N.*, *96*, 588.
Redman, R. O., and Shirley, E. G. 1937, *M. N.*, *97*, 416.
————. 1938, *ibid.*, *98*, 613.
Schwarzschild, K. and Villiger, W. 1907, *A. N.*, *174*, 137.
Seares, F. H., Ross, F. E., and Joyner, M. C. 1941, *Carnegie Institution*, Pub. 532.
Sérsic, J. L. 1957, *Observatory*, *77*, 146.
————. 1958*a*, *ibid.*, *78*, 24.
————. 1958*b*, *ibid.*, p. 123.
————. 1958*c*, *Revista Astronomica*, No. 143, pp. 65, 68.
————. 1958*d*, *ibid.*, Nos. 144-145, pp. 109, 113, 177.
————. 1959, *Zs. f. Ap.*, *47*, 9.
Shapley, H. 1934, *Harvard Bull.*, No. 895, p. 19.
Stock, J. and Williams, A. D. 1962, *Astronomical Techniques*, ed. W. A. Hiltner (Chicago: University of Chicago Press), chap. 17.
Vaucouleurs, G. de 1948, *Ann. d. Ap.*, *11*, 247.
————. 1953, *M. N.*, *113*, 134.
————. 1956*a*, *A. J.*, *61*, 430.
————. 1956*b*, *Occasional Notes*, No. 18, p. 130.
————. 1957, *Ann. La Houga Obs.*, Vol. *2*, Part I.
————. 1959*a*, *A. J.*, *64*, 397.
————. 1959*b*, *Ann. La Houga Obs.*, Vol. *2*, Part II.
Williams, R. C. and Hiltner, W. A. 1940, *Pub. Univ. Michigan Obs.*, *8*, 45.
————. 1941, *ibid.*, p. 103.
————. 1943, *Ap. J.*, *98*, 43.
Zwicky, F., Herzog, E., and Wild, P. 1961, *Catalogue of Galaxies and Clusters of Galaxies* (Zurich: California Institute of Technology), *1*.