THE ASTROPHYSICAL JOURNAL

VOLUME 145 JULY 1966 NUMBER 1

REDSHIFTS OF NINE RADIO GALAXIES INCLUDING THE ABNORMAL SYSTEM 3C 305

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received April 4, 1966

ABSTRACT

Redshifts have been obtained for nine radio galaxies. The values range from $\Delta\lambda/\lambda_0 = 0\ 0237$ to $\Delta\lambda/\lambda_0 = 0.2159$. The strongest emission lines that occur in the spectra are due to [Ne III], [Ne v], [O II], and [O III] and follow the pattern found previously by Minkowski for Cygnus A and by Schmidt for many other radio galaxies.

3C 305 appears to be a flattened, rotating galaxy with a faint, uniformly textured spiral arm. The tentative Hubble classification is Sa pec. The south edge of the galaxy is the near side, the east end of the major axis is approaching, and the spiral pattern is left-handed—circumstances which require that the arm is trailing. The emission lines show their maximum intensity 2000 pc eastward of the nucleus, suggesting a cone or jetlike distribution of gas, asymmetrically placed relative to the center of the galaxy. 3C 305 is a highly luminous optical galaxy with a radio power of 5×10^{41} ergs/sec. It is the first spiral-like system to be identified as a strong radio source.

I. INTRODUCTION

A program of multicolor photoelectric photometry of radio galaxies has recently been started with the 100- and 200-inch reflectors to study the redshift–apparent magnitude (Hubble) diagram for radio sources. At first, photometry was confined to the fifty radio galaxies whose redshifts have been reported in the literature (Schmidt 1965, thirty galaxies; Humason, Mayall, and Sandage 1956, nine galaxies; Minkowski 1960, 1961, 1963, six galaxies; Greenstein 1961, 1962, three galaxies; Lynds 1965, two galaxies), but during the course of the work many new optical identifications of radio galaxies became available through the efforts of Matthews (1964), Longair (1965), Véron (1965), Wyndham (1965, 1966), and others, in systematic search programs. Photometric data have now been obtained for some of these galaxies, and, in order to make a subsequent discussion of the Hubble diagram more complete, redshifts have been observed for nine of these new sources. We report here the new redshift data for the radio galaxies 3C 192, 223, 223.1, 287.1, 293, 296, 305, 371, and 390.3.

II. THE OBSERVATIONS

All spectra were obtained with the prime-focus spectrograph of the 200-inch telescope with either the 3-inch focal length f/1 solid Schmidt camera and a grating of 300 lines/mm, giving a dispersion of 400 Å/mm, or the 1.5-inch f/0.5 Schmidt camera with a grating of 600 lines/mm, giving a dispersion of 380 Å/mm. Most spectra were taken on baked Eastman Kodak IIaD plates which cover the region from λ 3100 to λ 6300 Å.

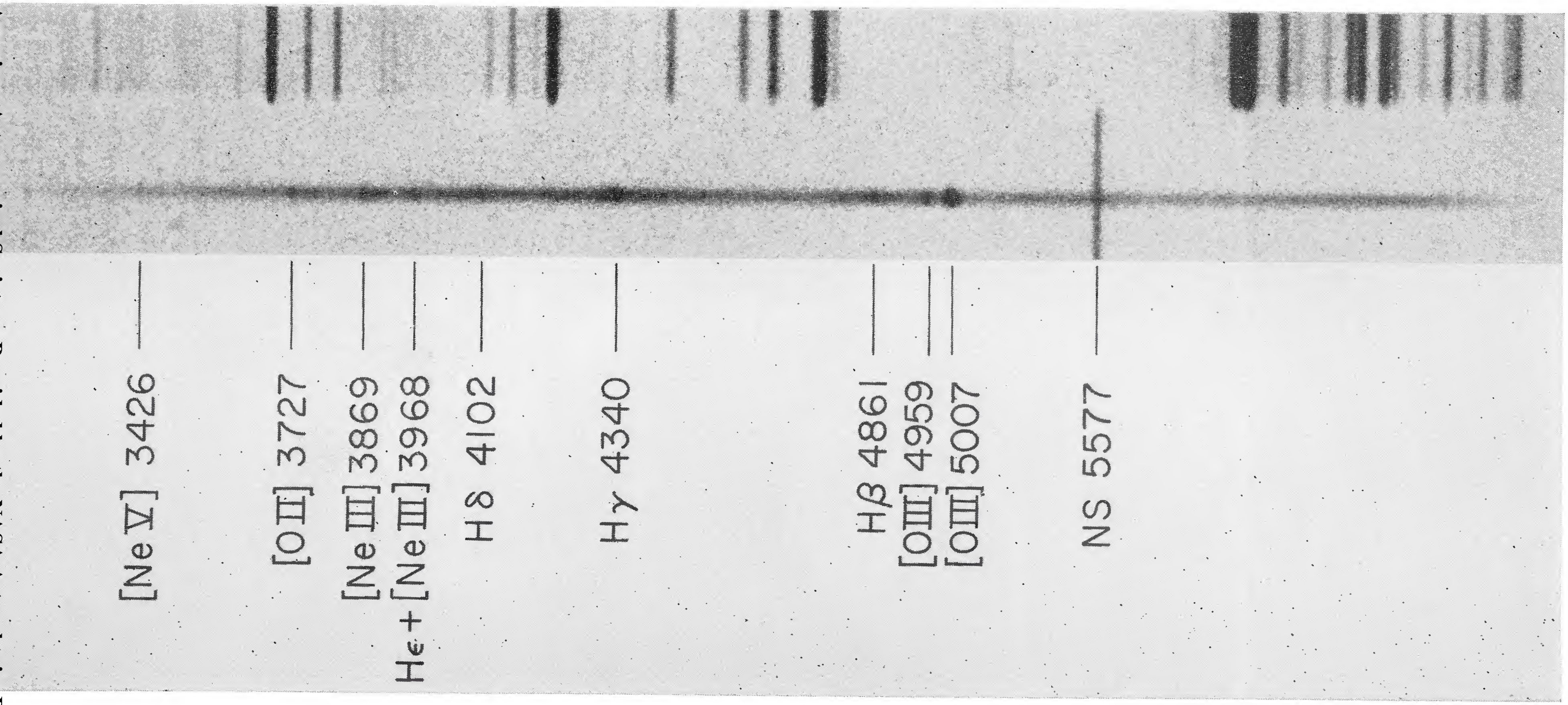

FIG. 1*a*.—The spectrum of 3C 390.3 taken with the 3-inch solid Schmidt camera on Eastman IIaD plates. The original dispersion was 400 Å/mm

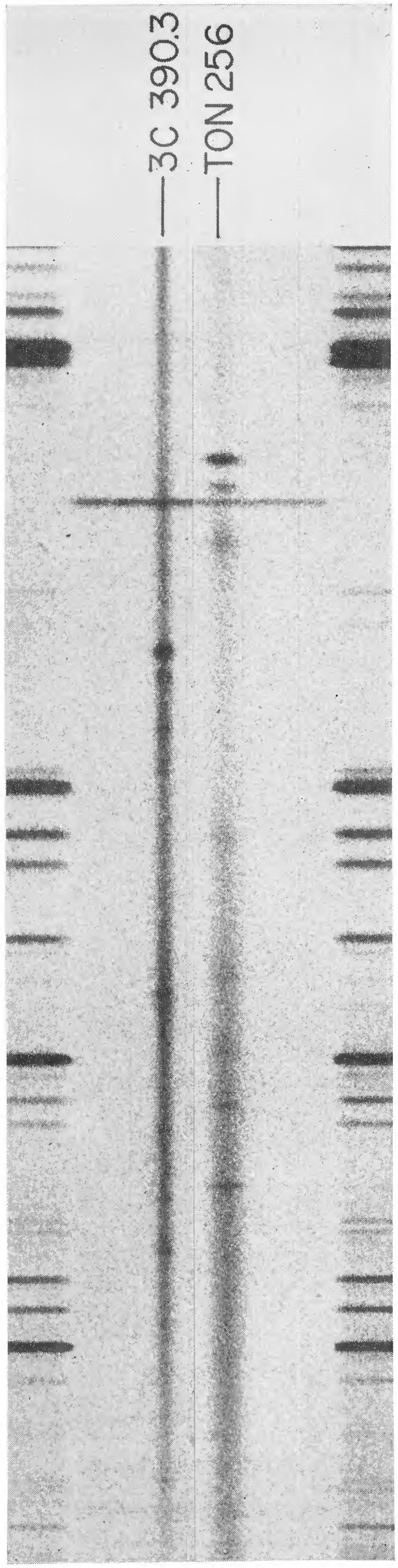

FIG. 1*b*.—Comparison of the spectra of 3C 390.3 with the radio quiet, quasi-stellar galaxy Tonantzintla 256

The exposure times ranged from 30 min to 150 min—long enough for emission lines to be clearly visible, but not long enough in general for absorption features to be detected. Emission lines were visible in all cases except 3C 296, where only the H- and K-lines and the G-band were visible.

Table 1 gives the results of the redshift determinations and a preliminary classification of galaxy type as estimated from the small-scale plates of the 48-inch Schmidt. Large-scale 200-inch plates were available for 3C 305. Finding charts for all nine sources are given by Wyndham (1965, 1966) in his summary listings. My attention was directed to most of the sources by Véron (1965) during the course of his identification program. The identifications of 3C 192, 3C 223, and 3C 305 were first made by Longair (1965), who very kindly made his results available before publication.

In addition to the redshifts, we list in Table 1 the visual magnitudes measured photoelectrically and corrected for aperture effect to an isophotal contour of about 25 mag. per square second of arc. Full details of the photometry and the Hubble diagram of nearly sixty radio galaxies will be discussed separately.

TABLE 1

REDSHIFTS FOR NINE RADIO GALAXIES

Object	Type	l^{II}	b^{II}	V_{25}	$\Delta\lambda/\lambda_0$ (Reduced to Sun)	$\Delta\lambda/\lambda_0$ (Corrected) for Galactic Rotation)	$c\Delta\lambda/\lambda_0$ (km/sec)	Remarks
3C192	E0	198	26	15 4	0 0599	0 0596	17880	2 em. lines
223	E2	188	49	17 1	1368	.1367	41010	6 em. lines
223.1	E5	183	49	16 4	.1075	1075	32250	3 em. lines
287.1	N	326	63	18 3	2159	.2156	64680	5 em. lines
293 .	D6?Sb?	54	76	14 3	0452	0454	13620	Only λ 3727 em. line
296 . .	E4	354	62	12 2	0237	0237	7110	H and K+G band, abs.
305	Sa?	103	49	13 6	0410	0416	12480	4 em. lines and H, K, G
371 .	N	100	29	. . .	0500	0508	15240	Only λ 3727 em. line
390.3	N	112	27	15 3	0 0561	0 0569	17070	9 em. lines

The redshifts, reduced to the Sun, are given in the sixth column of Table 1, while the values corrected for the motion of the Sun with respect to the local group of galaxies are tabulated in the seventh column. Guided by the results of Humason and Wahlquist (1955) and of Byrnes (1966), we adopt a solar motion of 300 km/sec toward $l^{II} = 90°$, $b^{II} = 0°$, giving a correction to $\Delta\lambda/\lambda_0$ of 0.001 sin l^{II} cos b^{II}, which is the same as adopted by Humason and Mayall in their redshift catalogue (1956) and by Schmidt (1965).

Comments on the individual sources follow:

3C 192: E0, brightest member of a small group. A weak spectrogram of 45-min exposure shows only λ 3727 [O II] and λ 5007 [O III], superposed on a weak continuum. The mean error of $\Delta\lambda/\lambda_0$ is ± 0.00013.

3C 223: E2 in a small group of fainter elliptical galaxies. The spectrum is rich in emission lines and closely resembles Cygnus A (Baade and Minkowski 1954; Schmidt 1965). The lines which were measured for redshift are λ 3426 [Ne V], λ 3727 [O II], λ 3869 [Ne III], λ 3968 [Ne III], λ 3861 Hβ, λ 4959 [O III], and λ 5007 [O III]. The mean error of $\Delta\lambda/\lambda_0$ is ± 0.0001.

3C 233.1: E5, either isolated or the brightest member (by 3 mag.) of a small group of very faint elliptical galaxies. Weak plate of 70-min exposure time shows λ 3727 [O II], λ 4959 [O III], and λ 5007 [O III] in emission. The mean error of the redshift is ± 0.0003.

3C 287.1: N galaxy, dominated by a Seyfert-type nucleus. An exposure of 135 min reveals the same spectral lines as in 3C 223. The redshift is the largest of the group and has a mean error of ± 0.0002. The photoelectric colors of $B - V = +0.92$, $U - B = -0.15$ show the typical ultraviolet excess characteristic of N-type galaxies.

3C 293: A highly flattened galaxy with a peculiar optical image. There are a small bright nucleus and an extensive outer envelope. The envelope is fainter on the southern half than on the northern and there may be some indication of spiral structure, but larger-scale plates are needed for an adequate description. A 2-hour exposure shows the continuum only faintly. A narrow line, undoubtedly due to λ 3737 [O II], is the only emission line seen. The redshift is based entirely on this feature.

3C 296: IC 5532. A large, bright E4, probably in a small group. No emission lines are visible. The redshift is based on the H- and K-lines and the G-band in absorption. The mean error is ± 0.0005.

3C 305: The optical object is described in the next section. The redshift is based on the four emission lines λ 3727 [O II], λ 3869 [Ne III], λ 4959 [O III], and λ 5007 [O III], together with H and K in absorption. The mean error is ± 0.00014. Both λ 3727 and λ 5007 are inclined on plates taken along the major axis, indicating rotation.

3C 371: N galaxy which appears completely starlike on visual inspection at the 200-inch. A strong continuous spectrum extends far into the ultraviolet. Two plates taken at 400 Å/mm with the 3-inch camera showed no convincing evidence for lines. A subsequent plate at 200 Å/mm, kindly taken by Greenstein, shows a definite emission line at λ 3914.6. After one knows it is there, one can see it on one of the lower-dispersion plates. The redshift of $z = 0.0500$ is based on an identification with λ 3727 [O II].

3C 390.3: The identification by Longair (1965) is not correct. Later work by Parker (Cambridge 1965, unpublished) shows the correct source, as does the work of Véron and of Wyndham. This is an N galaxy with at least one companion—that identified by Longair. The radio source looks entirely stellar to the eye at the 200-inch prime focus, but there is a faint outer envelope visible on photographs. The spectrum is the richest in emission lines of the nine sources studied, and is shown in Figure 1*a*. The four emission lines of shortest wavelength are sharp—no broader than the instrumental profile. However, λ 4340 (Hγ), λ 4959 [O III], and λ 5007 [O III] are about 50 Å wide, as in quasi-stellar sources.

Comparison of the spectrum of 3C 390.3 with the radio quiet quasi-stellar galaxy Ton 256 (Sandage 1965) is shown in Figure 1*b*. The colors of the objects are fairly similar: $B - V = +0.80$, $U - B = -0.59$ for 3C 390.3, and $B - V = +0.65$, $U - B -0.78$ (Iriarte 1959) for Ton 256.

III. THE ABNORMAL SYSTEM 3C 305

3C 305 appears as a normal elliptical galaxy on the 48-inch Schmidt plates, but large-scale photographs with the 200-inch show that the central region of the galaxy is crossed by a thin absorption lane, and that a general veil of obscuration exists across the western side of the central lens. Furthermore, there is a definite one-armed spiral structure of very low surface brightness and uniform texture which connects up with the dust lane. The Hubble classification would be Sa or Sa pec.

The spiral arm is left-handed; that is, as we proceed along the arm toward the nucleus, the direction of turning is counter-clockwise. The dust lane crosses the nucleus on the south side of the minor axis.

These features can be seen in Figure 2, which is a highly enlarged print from a blue-sensitive plate taken with the 200-inch. (The spiral arm is of such low surface brightness that the reproduction should be viewed from a distance of about 10 feet for best visibility).

3C 305 is obviously not a normal galaxy in the characteristics of its absorption lane. In most spiral systems of ellipticity 4 to 5 in which prominent lanes are visible against the

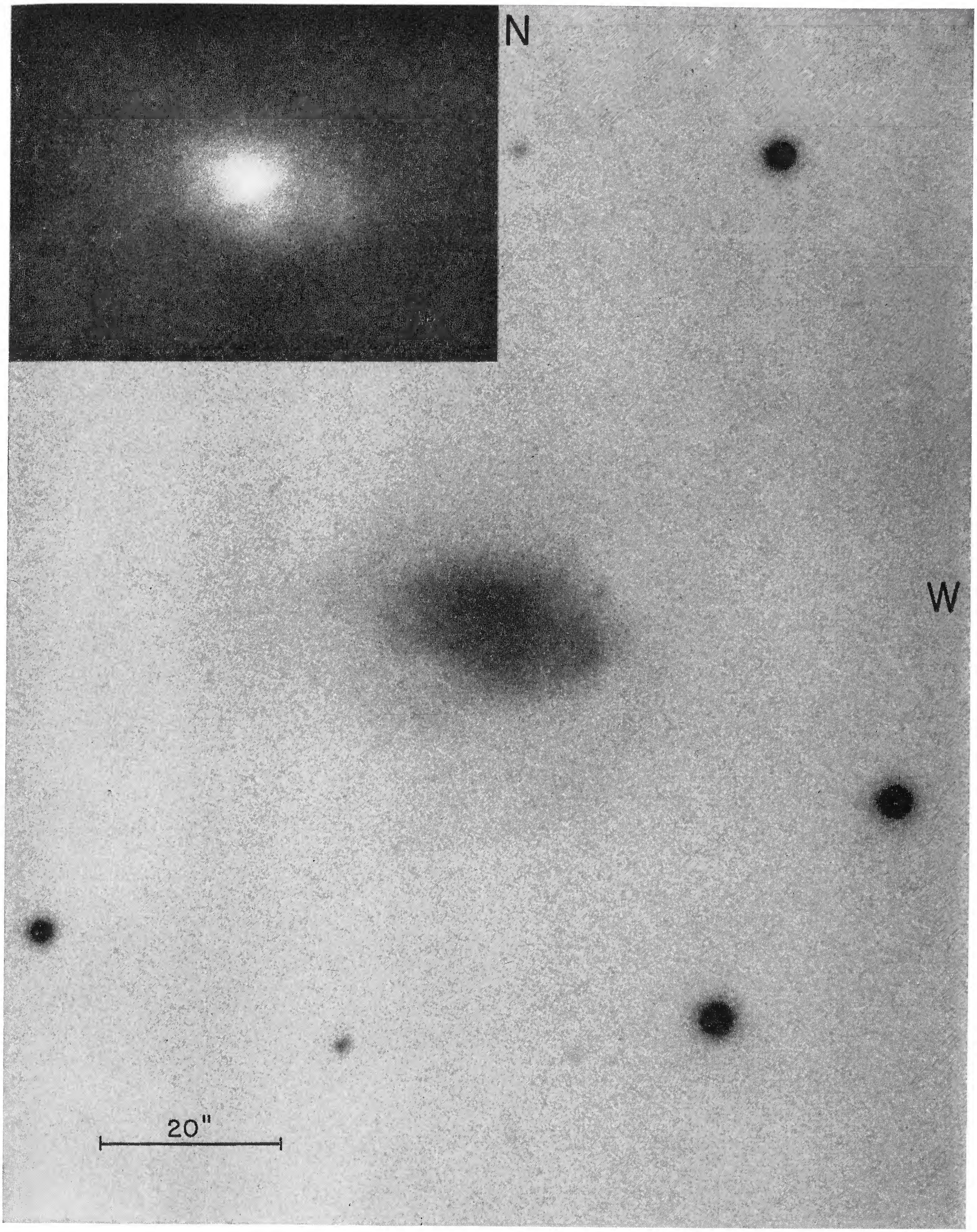

FIG. 2.—3C 305 from a 200-inch plate taken on Eastman 103aO emulsion behind a Schott GG13 filter. This reproduction should be viewed from about 10 feet to see the faint one-armed, left-handed spiral structure to best advantage.

nuclear light, the lanes do not cut into the lens at as abrupt an angle to the elliptical contour, nor as deeply into the nucleus as in Figure 2. The photographs which show the phenomenon best are those of Hubble (1943) and those reproduced by de Vaucouleurs (1958). We conclude from Figure 2 that the dust lane in 3C 305 is either (1) in the fundamental plane but quite non-circular in form, or (2) rises above the plane of the galaxy into the halo and is seen in projection against the central part of the lens. If the latter is the case, the lane cannot be used to show that the south side is nearest, but this conclusion does follow from the absorption patches on the south side along the minor axis where the spiral arm emerges from the lens.

Spectrograms of 3C 305 show another curious phenomenon. On a spectrogram taken with the slit placed along the major axis, the continuum radiation from the nuclear region showed strongly, as did the λ 3727 emission line of [O II], but the region of maximum intensity of this line was displaced along the slit (perpendicular to the dispersion) by 3″ from the nucleus toward the east, i.e., on the opposite side of the nucleus from the absorption lane. The effect is definite and beyond doubt. Additional plates were obtained which confirmed the feature. In all, six plates were taken at different position angles so as to trace the spatial distribution of λ 3727 across the face of the galaxy. The position angles, measured from north through east, were 30°, 70° (along the major axis—two plates), 90° (east-west), 115°, and 160° (nearly along the minor axis). The asymmetrical position of λ 3727 was seen on plates taken at position angles 70°, 90°, and 115° but is not seen at angles 30° and 160°. Although the angular spacing of the slit in position angle is not as fine as desired, the simplest interpretation of the present material is that a concentration of [O II] occurs eastward of the nucleus in a cone (or jet?) of about 60° total angle. The dispersion of the plates is insufficient to say anything about differential motions of the emission lines relative to absorption features to show if a radial expansion of the gas is occurring, but there is a suggestion of structure in the λ 3727 line as if two or more velocity systems may be present. Spectrograms of higher dispersion will be necessary to study the phenomenon adequately.

The best spectrogram of the series was taken with the 3-inch camera on a IIaD emulsion with the slit along the major axis. The λ 3727 and λ 5007 lines are both 10″ long—7″ on the east side and 3″ on the west side of the nucleus. The linear scale of 3C 305 is 606 pc per sec of arc, if the Hubble constant is 100 km/sec/10^6 pc. The total extent of the emission lines is therefore about 6000 pc—4200 pc on the east side and 1800 pc on the west side of the center.

Both emission lines are highly inclined on this plate, taken along the major axis, but the lines show no inclination on the spectrogram taken along the minor axis. The east side of the galaxy is approaching. This means that the spiral arm is trailing if the south edge of the galaxy is, in fact, the near side; but clearly 3C 305 does not add first class evidence to the data already accumulated on this problem (Slipher 1921; Hubble 1943; de Vaucouleurs 1958).

Measurement shows the angle of inclination of the emission lines to be 4°.2 for λ 3727 and 5°.1 for λ 5007, with an uncertainty of perhaps 0°.5. These angles, together with the dispersion of 400 Å/mm and the scale of the plate along the slit of 40″/mm, gives a velocity gradient of 59 km/sec/sec of arc for λ 3727, and 53 km/sec/sec of arc for λ 5007—values which are in good agreement considering the difficulty of the measurement. The average value of the rotational velocity is then 390 km/sec out to the 7″ limit to which the emission lines can be traced.

With a scale of 606 pc/sec of arc, the linear velocity gradient is $v/r = 9.2$ km/sec/100 pc. This is quite normal for galaxies in general, as can be seen from Mayall's study (1960) of seventy-two objects from similar-type material. Mayall tabulates the period for one rotation on the assumption of rigid-body motion. The rotation time and the gradient are related by

$$\frac{v}{r}=\frac{6.2\times 10^{8}}{t}\text{ km/sec/100 pc}$$

if t is expressed in years. The time for 3C 305 is then 6.8×10^7 years, which falls well within the range of Mayall's data. (Mayall's times should be decreased by a factor of 1.33 if a Hubble constant of 100 is used.) The foregoing is, of course, the crudest type of analysis because it assumes rigid-body rotation, but the very low dispersion used here does not permit a more refined measurement of the $v(r)$ function.

3C 305 is particularly interesting as a radio source because it appears to be the first example of a flattened, rotating galaxy with spiral arms that is a strong radio emitter. The absolute radio power, obtained by integrating the radio spectrum from 10^7 to 10^{10} hertz using a spectral index of -0.68, is $L_R = 4.7 \times 10^{41}$ ergs/sec, again adopting a Hubble constant of 100 km/sec/10^6 pc. Although not one of the strongest sources, it is more powerful than any other spiral galaxy identified to date (see Matthews, Morgan, and Schmidt 1964). The optical luminosity is $M_V = -21.99$, $M_B = -21.22$, which is to be compared with $\langle M_V \rangle = -21.60$, $\langle M_B \rangle = -20.77$ for the mean absolute magnitude of fifty-five radio galaxies where photometry and redshifts are now available (Sandage 1966).

Finally, the linear dimensions of the optical image are quite large. The main body, with a diameter of 15″ by 27″, is 8500 pc by 16000 pc in linear extent, while the outer spiral structure has a diameter of 42″ by 55″, which corresponds to 25000 pc by 33000 pc. These dimensions indicate a supergiant system.

It is a pleasure to thank Phillipe Véron for providing finding charts for these and many other radio sources found during the course of his identification program. I am also indebted to him for measurement of five of the spectrograms, and to Jesse Greenstein for obtaining the excellent plate of 3C 371.

REFERENCES

Baade, W., and Minkowski, R. 1954, *Ap. J.*, **119**, 206.
Byrnes, D. V. 1966, *Pub. A.S.P.*, **78**, 46.
Greenstein, J. L. 1961, *Ap. J.*, **133**, 335.
———. 1962, *ibid.*, **135**, 679.
Hubble, E. P. 1943, *Ap. J.*, **97**, 212.
Humason, M. L., Mayall, N. U., and Sandage, A. R. 1956, *A.J.*, **61**, 97.
Humason, M. L., and Wahlquist, H. D. 1955, *A.J.*, **60**, 254.
Iriarte, B. 1959, *Lowell Obs. Bull.*, **101**, Table 1.
Longair, M. S. 1965, *M.N.*, **129**, 419.
Lynds, R. 1965, Reported at the Miami Conference on Cosmology (December).
Matthews, T. A. 1964, *Carnegie Institution Yearbook*, **63**, 44–45.
Matthews, T. A., Morgan, W. W., and Schmidt, M. 1964, *Ap. J.*, **140**, 35.
Mayall, N. U. 1960, *Ann. d' ap.*, **23**, 344.
Minkowski, R. 1960, *Ap. J.*, **132**, 908.
———. 1961, *A.J.*, **66**, 558.
———. 1963, quoted by Maltby, P., Matthews, T. A., and Moffett, A. T. 1963, *Ap. J.*, **137**, 153, Table 1.
Sandage, A. 1965, *Ap. J.*, **141**, 1560.
———. 1966, in preparation.
Schmidt, M. 1965, *Ap. J.*, **141**, 1.
Slipher, V. M. 1921, *Pop. Astr.*, **29**, 272.
Vaucouleurs, G. de. 1958, *Ap. J.*, **127**, 487.
Véron, P. 1965, results incorporated in the summary list of Wyndham (1966).
Wyndham, J. D. 1965, *A.J.*, **70**, 384.
———. 1966, *Ap. J.*, **144**, 459.