THE ROTATION AND PHYSICAL CONDITIONS IN THE SEYFERT GALAXY NGC 7469

E. MARGARET BURBIDGE AND G. R. BURBIDGE
University of California at San Diego, La Jolla

AND

K. H. PRENDERGAST*
NASA Institute for Space Studies, New York
Received November 14, 1962

ABSTRACT

A spectroscopic study of the Seyfert galaxy NGC 7469 and its companion IC 5283 has been made. IC 5283 is a peculiar, irregular galaxy with spectral characteristics similar to those seen in many systems described by Vorontsov-Velyaminov. NGC 7469 has a recession velocity of +5075 km/sec and a nucleus with a maximum diameter of 460 pc (this size is limited by seeing), in which strong emission lines arise; the hydrogen lines have very broad wings, corresponding to Doppler motions of ± 2500 km/sec. In addition to this, short-exposure spectra show that there is a rotating component of the gas with a diameter of about 1800 pc. Spectra of longer exposure show emission lines extending to a distance of about 3600 pc from the center. A rotation-curve out to this distance has been constructed, and analysis of this shows that the total mass interior to about 3600 pc is $\sim 1.1 \times 10^{10} M_{\odot}$. It is found that the escape velocity from this central region is much less than the velocities indicated by the broadening of the hydrogen lines from the nucleus. Thus it is concluded that gas is escaping from the nuclear regions. The galaxy closely resembles the Seyfert galaxy NGC 1068 in its structure. Some discussion of the criteria for classification of a Seyfert galaxy is given. The very difficult problem of the time scale to be associated with the Seyfert galaxies is briefly discussed.

I. INTRODUCTION

NGC 7469 is one of the very few galaxies that have small, very bright nuclei and whose spectra are characterized by strong emission lines of great breadth and, sometimes, high excitation. Seyfert (1943) drew attention to the existence of this type of galaxy; he gave a list of twelve galaxies in this class, namely, NGC 1068, 1275, 2782, 3077, 3227, 3516, 4051, 4151, 4258, 5548, 6814, and 7469, and he investigated in detail six of the brightest of these.

It is first worthwhile specifying the criteria which, in our opinion, must be satisfied if a galaxy is to be placed in the Seyfert group. These are as follows:

(i) It has a small bright nucleus.

(ii) The spectrum of the nucleus contains emission features which are not normally seen in the spectra of galaxies. Some of these should be lines indicating higher excitation than that required to excite [O III] and [Ne III]. Surveys of the emission features seen in general in irregular, spiral, and elliptical galaxies (Humason, Mayall, and Sandage 1956; Mayall 1958; Burbidge and Burbidge 1962*a*, *b*) show that the features normally seen are only Hα, [O II] λ 3727, [N II] λ 6583, λ 6548, [S II] λ 6716, λ 6731, and (less frequently) [O III] λ 4959, λ 5007.

(iii) The emission features, or at least the hydrogen emission lines, must be of great width, which, if interpreted as Doppler motions, corresponds to velocities in the range ± 500 to ± 4250 km/sec, according to Seyfert.

There are many galaxies which satisfy the first criterion alone. However, it is probable that some of the Seyfert galaxies have higher surface brightnesses of their nuclei than any other systems known. This as yet is only a qualitative statement. Apart from the Seyfert objects, the only galaxies whose spectra satisfy criterion ii[1] are some of the

* NAS-NASA resident research associate.

[1] Here we exclude the spectra of separate gaseous nebulae which can be obtained in nearby galaxies such as M31 and M33, since we are considering spectra integrated over dimensions of the order of 100 pc or greater and are specifically considering nuclei.

ones which are associated with strong radio sources. However, these do not have the tremendous broadening described under iii. The Seyfert galaxies alone satisfy iii. This, then, could be chosen as the overriding criterion.

Clearly galaxies of this type are rare. Of the twelve listed by Seyfert, only eight certainly satisfy the criteria given above, which are essentially those used by Seyfert. We mention briefly the reasons why NGC 2782, 3077, 4258, and 6814 should be removed from this category. NGC 2782 is a barred spiral showing fast rotation (Duflot-Augarde 1960) and does not have the very broad emission lines characteristic of true Seyfert galaxies or lines of high excitation. A spectrum obtained with the B spectrograph at the prime focus of the McDonald telescope showed strong, rotationally inclined Hα emission, [N II] λ 6583, Hβ, and [O II] λ 3727. NGC 3077, an irregular member of the M81 group, does not have broad emission lines or high-excitation lines, nor does NGC 4258, an Sb spiral currently being studied by us in order to obtain its rotation-curve and mass distribution. NGC 6814 is a face-on spiral; one not very strongly exposed spectrum obtained with the B spectrograph at the prime focus of the McDonald telescope showed only narrow Hα and [N II] emission lines; so probably this is also not a Seyfert galaxy. However, one galaxy which should probably be added to this category, since it has moderately broad emission lines, very strong [O III], and the high-excitation Fe VII λ 6086, is a component of one of Vorontsov-Velyaminov's catalogue of interacting galaxies (Vorontsov-Velyaminov 1959). It is the brightest member of the chain of galaxies, VV 150; data on this object will be presented in another paper. (Here we just wish to note that one of Vorontsov-Velyaminov's catalogue of 355 interacting galaxies has been found to be probably a member of the rare class of Seyfert galaxies.)

Despite their rarity, the Seyfert galaxies are probably of great significance from the point of view of the structure and evolution of the central regions of galaxies. The broadening of the emission features appears to be Doppler widening, and, if this is so, then it must be attributable to very large disordered motions in the gas. The values tabulated by Seyfert for the six galaxies studied by him give the correct order of magnitude, although the maximum spread may not be quite as large as listed there (in NGC 7469 we find a spread of ± 2500 km/sec, rather than ± 4250 km/sec). The high-excitation lines show that the electron density and temperature in these nuclei are rather similar to those in planetary nebulae. The great strength of the lines shows that a very large amount of energy is being radiated through the lines.

We have earlier studied a member of this group, NGC 1068 (Burbidge, Burbidge, and Prendergast 1959), in order to try to obtain information about the mass and the dynamical conditions in the central region by measuring the rotation in the galaxy. It was found possible to measure the rotation in a region between 10″ and 25″ (i.e., between 800 and 2000 pc) from the center. The rotation right in the nucleus could not be measured because of the width of the emission lines. From the analysis of the rotation, the mass distribution in the galaxy was found to be such that the velocity of escape at the center was about 410 km/sec, very much less than the disordered motion indicated by the emission lines. Consequently, we concluded that gas must be escaping from the nuclear region of NGC 1068. We did not estimate the rate at which mass was being lost from the central region; however, the fact that some mass was being lost, together with the fact that large random motions had been generated and great amounts of energy were being radiated in the emission lines, together showed that the nucleus must be evolving rapidly, if the energy was supplied by nuclear processes in stars. The Seyfert objects might thus be thought to be a class of galaxies in which the central regions are passing through a short-lived but extremely active phase.

An alternative approach to this problem was proposed by Woltjer (1959), who suggested that the tiny nuclei might be very massive and dense, with mass-to-light ratios of about 25. The great breadth of the emission lines would then be due not to disordered motions but to rapid rotation, unresolved on the photographic plate because of the smallness of the nuclei and thus seen as a great broadening of the lines. In a note at the end of his paper, however, Woltjer excluded NGC 1068 from this proposal partly because of the results described above, in which the nuclear mass was not found to be so very large. In view of the results obtained for NGC 1068, it seemed important to investigate other galaxies of this type to try to throw light on the dynamical conditions in the nuclei. Of the eight galaxies in Seyfert's list which have the broad emission lines, NGC 1275 is a special case, which has been studied by Minkowski (1957). It is a radio source which is strong when compared with our own Galaxy and other normal spirals (as, of course, is NGC 1068); it is not suitable for the study of the mass distribution from the rotation-curve because Minkowski's analysis showed that there are probably two masses involved, in a highly complex system.

After NGC 1068, the two galaxies which appear most favorable for study because of their orientation and the luminosity of their spiral structure outside the nucleus are NGC 3227 and NGC 7469. Data on the former will be presented elsewhere. We describe here our study of NGC 7469.

TABLE 1

LIST OF SPECTRA

Spectrum No	Date	Object	P A. of Slit	Exposure (minutes)	Dispersion (A/mm)	Slit Length
McD B 603	Dec. 6, 1959	NGC 7469+IC 5283	28°	174	330	290″
Lick 178	June 6, 1962	NGC 7469	121°	104	375	2′
Lick 185	June 8, 1962	NGC 7469	121°	107	375	2′
Lick 249	Sept. 22, 1962	IC 5283	123°	120	375	3′
Lick 267	Sept. 25, 1962	NGC 7469	121°	20	195	2′
Lick 268	Sept 25, 1962	NGC 7469	121°	5	195	2′
Lick 269	Sept. 25, 1962	NGC 7469	31°	10	195	2′

II. OBSERVATIONS AND DESCRIPTION OF RESULTS ON NGC 7469

NGC 7469 has been classified Sa by Humason, Mayall, and Sandage (1956). It has a companion, IC 5283, 80″ distant from it, which is discussed in Section III; here we just wish to note that the radial velocity of IC 5283 shows it to be definitely a physical companion of NGC 7469. A plate of both galaxies, taken at the prime focus of the 120-inch telescope at the Lick Observatory, is shown in Figure 1. NGC 7469 has the small, intensely bright nucleus characteristic of Seyfert galaxies, an inner spiral structure about 33″ in diameter, and a faint outer ring about 100″ in diameter, with its major axis in the same position angle as that of the major axis of the inner spiral structure, namely, 121°. We have concluded that this is the position angle of the line of nodes of the galaxy.

A preliminary spectrum was taken with the B spectrograph at the prime focus of the McDonald 82-inch telescope in December, 1959, with the slit set in P.A. 28° to go through the nucleus of NGC 7469 and the brightest part of IC 5283. Although the exposure was nearly 3 hours, only a trace of continuous spectrum of IC 5283 was recorded. The spectrum of the nucleus of NGC 7469 was strong over the whole range photographed, i.e., λ 6850–λ 3600. It showed Hα, Hβ, Hγ, [O III], [O II], [N II], [S II], and [O I] in emission, but no absorption features were definitely identified (see later discussion). It was clear from this spectrum that more light-gathering power and greater scale were needed, and observations were therefore not pursued with the McDonald telescope.

In June and September, 1962, six spectra, which are listed in Table 1, were obtained with the new prime-focus spectrograph of the 120-inch telescope at the Lick Observatory. This instrument is somewhat similar to the B spectrograph, but it has a variety of

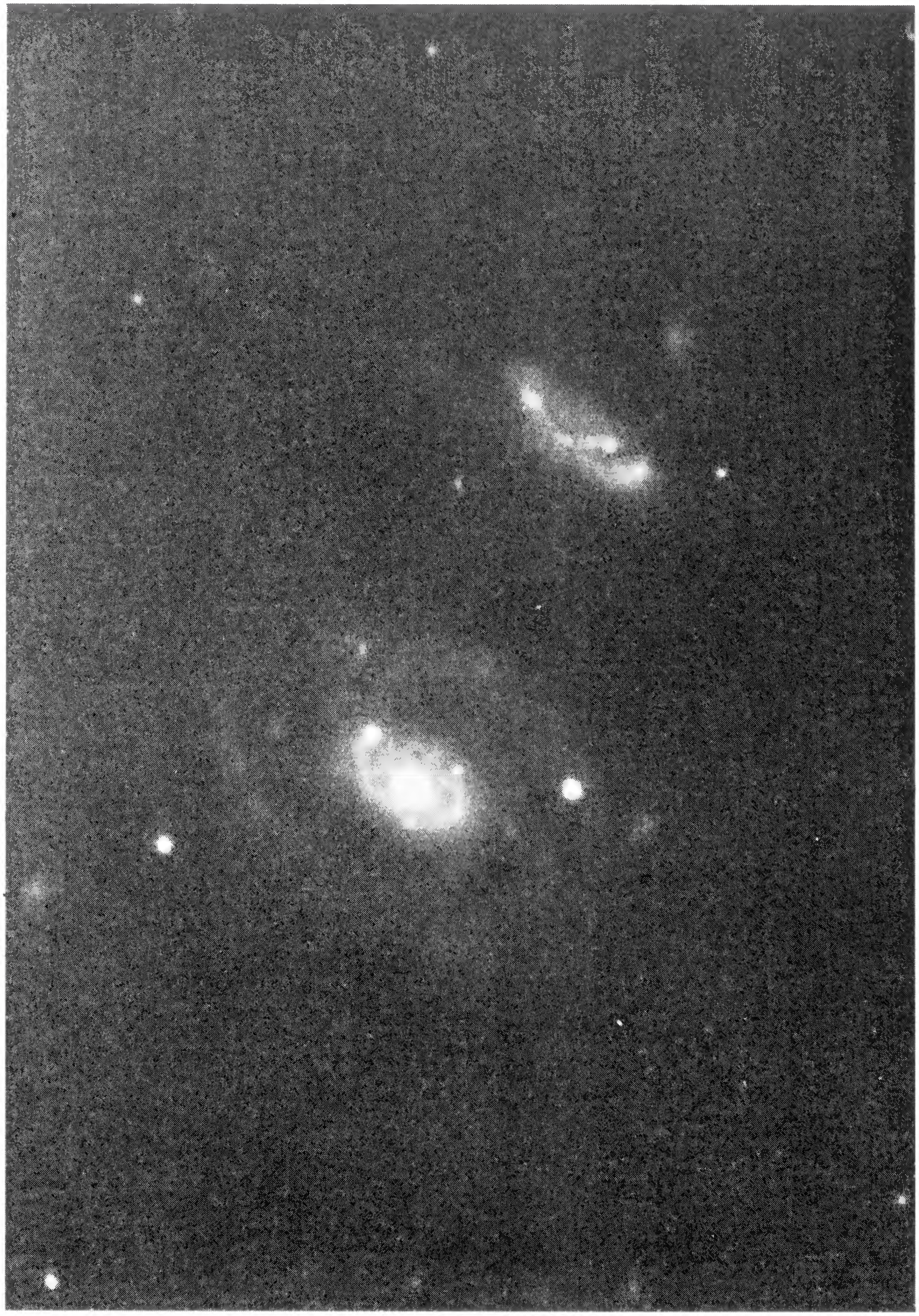

FIG. 1.—NGC 7469 and IC 5283. Plate taken at prime focus of Lick 120-inch telescope. Eastman Kodak 103a-O plate, no filter. North is at top, west at left. Scale: 1 mm = 1″.5.

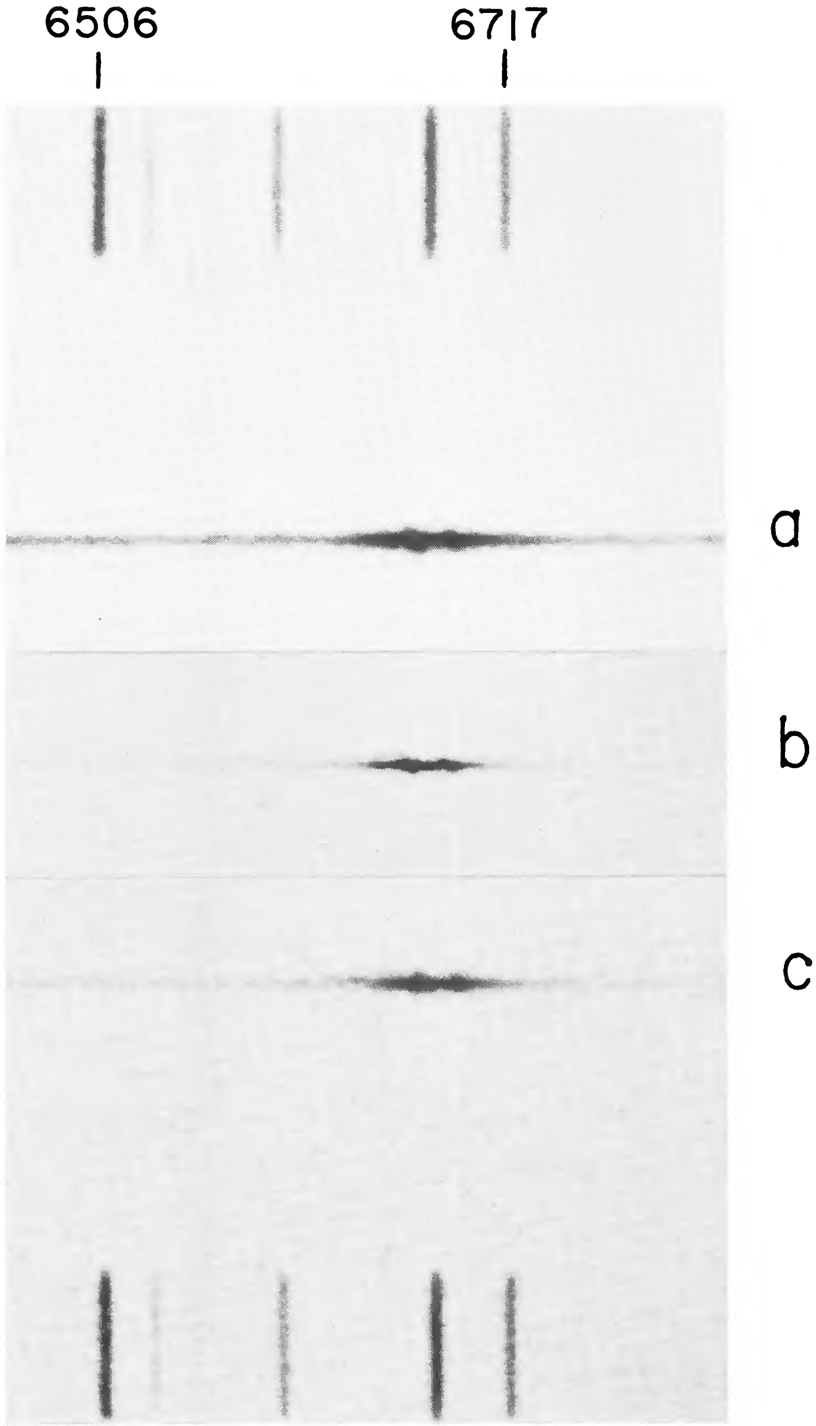

FIG. 2.—Spectrum of nucleus of NGC 7469, showing broad Hα (λ 6563) and [N II] λ 6583 emission with narrower emission cores, tilted in (*a*) and (*b*) but not in (*c*). *a:* Spectrum No. 267, 20^m exposure, P.A. 121°. *b:* Spectrum No. 251, 5^m exposure, P.A. 121°; this has no comparison spectrum and is not listed in Table 1, as it could not be measured. *c:* Spectrum No. 269, 10^m exposure, P.A. 31°. Wavelengths of two Ne comparison lines are shown.

gratings and cameras, and guiding can be done very accurately by means of an off-set guide star. We used the thick Schmidt camera and the gratings giving, with this camera, dispersions in the Hα region of about 375 and 195 A/mm. Kodak 103*a*-F plates were used. The curved focal plane was photographed on flat plates; consequently, the best focus for the spectral region being observed had to be chosen. The curvature correction was obtained by taking spectra which had the neon comparison source across the object window, as well as in the usual position at either side of the object window. All spectra were measured with the new Mann two-co-ordinate measuring instrument at the University of California, with the perpendicular cross-wires set at 45° to the direction of travel of the screws, as we have always done in measurement of spectra of galaxies.

On two of the Lick spectra, Nos. 178 and 249, which were both taken with the grating giving 375 A/mm, the night-sky line [O I] λ 6300.23 was strong enough to measure as a check on systematic errors. On No. 178, the mean of nine settings along the length of the 2′ window was 6300.10, giving an error of −0.13 A. The average deviation of the measures along the length of the line was ±0.33 A, and there was no systematic run from one side of the window to the other. On No. 249, the mean of twelve settings along the length of the 3′ window was 6300.45, giving an error of +0.22 A. The average deviation of the measures along the length of the line was ±0.37 A, and again there was no systematic run across the window. Finally, the McDonald spectrum B 603 also showed the [O I] λ 6300.23 line across its 5′ window; the mean wavelength measured was 6300.41, giving an error of +0.18 A, with an average deviation of the measures across the window of ±0.30 A.

Table 1 shows that four of the Lick spectra were taken with the slit in position angle 121°, along the major axis of NGC 7469. One was taken perpendicular to this setting. For the spectrum of IC 5283, the slit was set through the brightest condensations of this galaxy; this direction happens to be nearly parallel to the major axis of NGC 7469.

The low-dispersion Lick spectrum No. 185 of NGC 7469 shows weak Hα and [N II] λ 6583 emission from the positions where the slit crosses the inner spiral arms outside the nucleus. Spectrum No. 178 also shows this, but the lines were weaker, and only Hα on the southeast side could be measured. The short exposures with the higher dispersion were taken in the hope that, with the accurate guiding possible with this instrument, the velocities given by the central core component of the emission lines in the nucleus of the galaxy (whose presence was noted by Seyfert) could be measured if they were not blotted out by the overexposed broad emission lines. This was indeed found to be the case; Hα and the [N II] lines λ 6583, λ 6548 were found to have a narrow core with considerable tilt due to the rotation of the nuclear region. In Figure 2 we show reproductions of the short-exposure spectra in position angles 121° and 31°, along and at right angles to the major axis. The tilt of the features in the spectra along the major axis is clearly seen, while no tilt is detected in that perpendicular to the major axis. We are therefore justified in concluding that the tilt of the spectrum lines is due to rotation of the nucleus.

Measures at right angles to the dispersion in the short-exposure spectra show (1) that the width of the continuous spectrum in the nucleus at about λ 6400, coming from the stars in the nucleus, is 1″.4; (2) that the width of the broad emission between the narrow cores of Hα and [N II] λ 6583 and outside λ 6583 and λ 6548 is about 2″.3, with some uncertainty; (3) that the emission cores extend well outside the region where the broad emission comes from, and the extreme extent of the Hα core is about $5\frac{1}{2}''$. The spectra were obtained in good, but not exceptional, seeing; we conclude that the stellar continuum comes from a region that may actually have a smaller diameter than $1\frac{1}{2}''$, which is probably set by the seeing. The disordered motions come from the central region, of slightly larger diameter than the stellar nucleus. On the other hand, the ordered rotational velocities come from a region of larger diameter than the region where the disordered motions are measured.

If the stars in the central nucleus give rise to an absorption-line spectrum and are moving with the velocity dispersion characteristic of the central regions of normal spiral galaxies, we should see absorption lines in the nuclear spectrum which would be much narrower than the great widths of the hydrogen emission lines produced in the gas in the nucleus. This was the case in NGC 1068, where Seyfert noted that the Ca II λ 3933 line was not significantly wider than in the elliptical galaxy M32. However, he found that this line was very shallow and at least 50 A wide in NGC 7469. We have not been able to confirm this, since we cannot detect any absorption features, even Ca II λ 3933, on our McDonald spectrum of NGC 7469, which covers the photographic region, though with low dispersion. Also no sign of the absorption blend of the Na I D lines is seen on the Lick spectra.

III. IC 5283, THE COMPANION OF NGC 7469

IC 5283 is shown in Figure 1 and is obviously very irregular in form. In its appearance, it resembles some of the objects listed in the *Atlas of Interacting Galaxies* (Vorontsov-Velyaminov 1959), but it is not, however, included in that *Atlas*. We obtained the spectrum in order to find out whether it is a physical companion to NGC 7469. The slit of the spectrograph was set in position angle 123°, as this orientation will go fairly well

TABLE 2

VELOCITIES MEASURED IN IC 5283
(L 249, P.A. 123°)

	Distance from Center of Strongest Continuum (seconds of arc)	Velocity (km/sec)
Hα	SE. − 3 4	+4933
	− 1 3	+4899
	+ 0 8	+4865
	+ 2 9	+4796
	+ 4 2	+4710
	+ 7 6	+4641
	+ 9 1	+4658
	+11 2	+4727
	NW. +13 3	+4899
[N II] λ 6583	SE. − 0 6	+4892

through the three brightest condensations or knots, which are nearly in line. Actually, the slit passes just southwest of the brightest part of the central condensation, but the width of the slit (2″.7) means that light coming from this extent is integrated. On the resulting spectrum, covering the wavelength region 5900–6850 A, each of these knots gave rise to a strip of continuum, that from the central (and apparently weakest knot in Fig. 1, which is from a 103*a*-O plate) being the strongest in the red-wavelength region. This central knot and the knot at the northwest end of the object showed Hα in emission, and this emission line extended between the two knots, with a break halfway between them, and also a little way to the southeast side of the central knot, but not on the other side of the northwest knot. The line [N II] λ 6583 was seen in the central knot only. The knot at the southeast end of the object showed no Hα or [N II] at all, but only a continuous spectrum.

From the spectrum it appears that IC 5283 is actually a double, or even triple object. The Hα emission line is in two halves, and each half shows rotation. The measured velocities are listed in Table 2 as a function of distance from the center of the continuum coming from the central condensation. The velocity from the northwest knot at the point in the center of its continuum is +4899 km/sec, and this velocity then decreases by about 250 km/sec, after which there is a break in the emission line. When the line can be measured again, the recession velocity is +4710 km/sec, and this velocity increases until, at the center of the continuum coming from the central condensation, it is about +4875 km/sec. The velocity of the southeast condensation, in which we were not able to record Hα, is not known.

The recession velocities of the two knots at the positions where the continuous spectrum is produced show, without doubt, that IC 5283 forms a physical system with NGC 7469. The central velocity of NGC 7469 is shown in the next section to be +4868 km/sec. The approximately cylindrical form of the various parts of IC 5283, with strong knots at the end, and the faint tail extending from one end of the central condensation (this tail can be seen in Fig. 1), together with the measured rotation, suggest that the object may be of fairly recent origin. It bears some similarity, in its form and in the run of the rotations, to NGC 4676 (Burbidge and Burbidge 1961). The question of cylindrical condensations as an early stage in the formation of galaxies will be discussed in a later paper (Burbidge, Burbidge, and Hoyle 1963).

IV. THE ROTATION OF NGC 7469

The measured velocities from the Lick spectra are given in Table 3; these are not corrected for rotation of our Galaxy. As can be seen from Table 3, five values have been obtained for the recession velocity of the center of the galaxy. These are +4889, +4850, +4866, +4851, and +4883 km/sec, and their mean is +4868 km/sec. On the long-exposure Lick spectra, the emissions from the nuclear regions were so overexposed that no attempt was made to measure the central velocity on these. In the McDonald spectrum, the centers of the broad emissions of Hα, [N II] λ 6583, [O I] λ 6300, [O III] λ 5007, λ 4959, Hβ, and [O II] λ 3727 were measured; there was considerable scatter, as might have been expected in the measurement of such broad lines, but the result from these measures for the recession velocity of the center is $+4840 \pm 113$ (a.d.) km/sec. Thus this value is in satisfactory agreement with the mean recession velocity obtained from the Lick spectra. The recession velocities given by Humason, Mayall, and Sandage (1956) are $+4780 \pm 40$ km/sec (Humason) and $+4692 \pm 140$ km/sec (Mayall). We have taken the central velocity to be +4868 km/sec, this being the value from the Lick spectra. This value has been subtracted from all the velocities, and the negative values have been reflected about the center. The resulting points have been plotted as a rotation-curve, which is shown in Figure 3.

Although it appears from this plot that the inner part of the rotation-curve is defined only by the central velocity and the set of points all lying between 1$''$.8 and 2$''$.3 from the nucleus, it must be remembered that the rotation seen in Figure 2 appears to be continuous and linear across the nucleus, as far as the small scale allows this to be judged. The equivalent of only one setting outside the center has been made for each side of the center for each line because the usual interval perpendicular to the dispersion at which we have made settings in measurement is 20–25 μ on the photographic plate, or about 1$''$.7–2$''$.1. The limit to the accuracy in an object as small as this is the seeing and the resolution on the photographic plate.

It will be seen that the rotation appears to reach a maximum and flatten off beyond about 5$''$ from the nucleus. The two sides do not appear to be symmetrical. Apparent asymmetries in the rotation-curves have been seen in other galaxies. However, in this case the scale is so small that the effect may not be real.

We have carried out a standard analysis of the rotation as described in our series of papers published since 1959 in this *Journal* on the rotations of galaxies. The model that is used corresponds to a series of similar spheroids with non-uniform density, and it is necessary to solve the integral equation

$$V^2(\varpi) = 4\pi G(1-k^2)^{1/2}\int_0^{\varpi} \frac{\rho(a)\,a^2 da}{(\varpi^2 - k^2 a^2)^{1/2}},$$

using power-series expansions in V^2 and ρ. The solutions have been made on the IBM 7090 at the Institute for Space Studies. The curves corresponding to the insertion of three or four parameters are shown in Figure 3. The corresponding density-curves for an assumed value of c/a of $\frac{1}{5}$ are shown in Figure 4.

The mean recession velocity for the center was +4868 km/sec; when this is corrected for galactic rotation by the same formula as that used by Humason *et al.* (1956), this becomes +5075 km/sec. For an assumed value of the Hubble constant of 75 km/sec per Mpc, this gives a distance of 67.7 Mpc, so that 1″ = 328 pc.

The inclination of the galaxy is measured by ξ, the angle between the normal to the plane of rotation and the line of sight. From the ratio of the apparent lengths of major and minor axes we find in this case that $\xi = 49°$. To obtain the mass, we must multiply

TABLE 3

VELOCITIES MEASURED IN NGC 7469

	Distance from Center (seconds of arc)	Velocity (km/sec)
	L 178, P A 121°	
Hα	SE. −10 6	+4798
	L 185, P A 121°	
Hα	SE. − 9 0	+4765
	+ 6 5	+4988
	+ 8 5	+5022
	NW. +10 6	+5022
[N II] λ 6583	SE. −10 8	+4807
	− 8 7	+4790
	L 267, P A 121°	
Hα	SE. − 2 3	+4721
	NW. + 2.2	+5022
[N II] λ6583	SE. − 1 9	+4785
	NW. + 1 9	+4943
[O I] λ 6300	0	+4889
	L 268, P A. 121°	
Hα	SE. − 1 8	+4769
	0	+4866
	NW. + 1.8	+4990
[N II] λ 6548	0	+4850
	L 269, P.A. 31°	
Hα	SW. − 2 2	+4869
	0	+4851
	NE. + 1.8	+4860
[N II] λ 6583	0	+4883

the values obtained from integrating the density-curve by $\operatorname{cosec}^2 \xi = 1.7718$. If we do this for the three- and four-parameter solutions and an assumed c/a of $\frac{1}{5}$, we obtain masses of 1.18 and $1.11 \times 10^{10}\ M_\odot$, respectively, for the mass within $11'' = 3.6$ kpc. We have assumed a fairly large value for the c/a ratio because this mass is that of the central bulge of the galaxy. However, even if we put $c/a = \frac{1}{15}$, the values are only changed to 1.19 and $1.12 \times 10^{10}\ M_\odot$, respectively.

V. THE PHYSICAL CONDITION IN THE CENTRAL REGION OF NGC 7469; COMPARISON WITH NGC 1068

The spectroscopic features which can be seen and measured in this galaxy are rather similar to those described in NGC 1068. However, the fact that NGC 1068 is some four times closer to us than is NGC 7469 means that the scales involved are significantly different. Let us distinguish the various features which may exist.

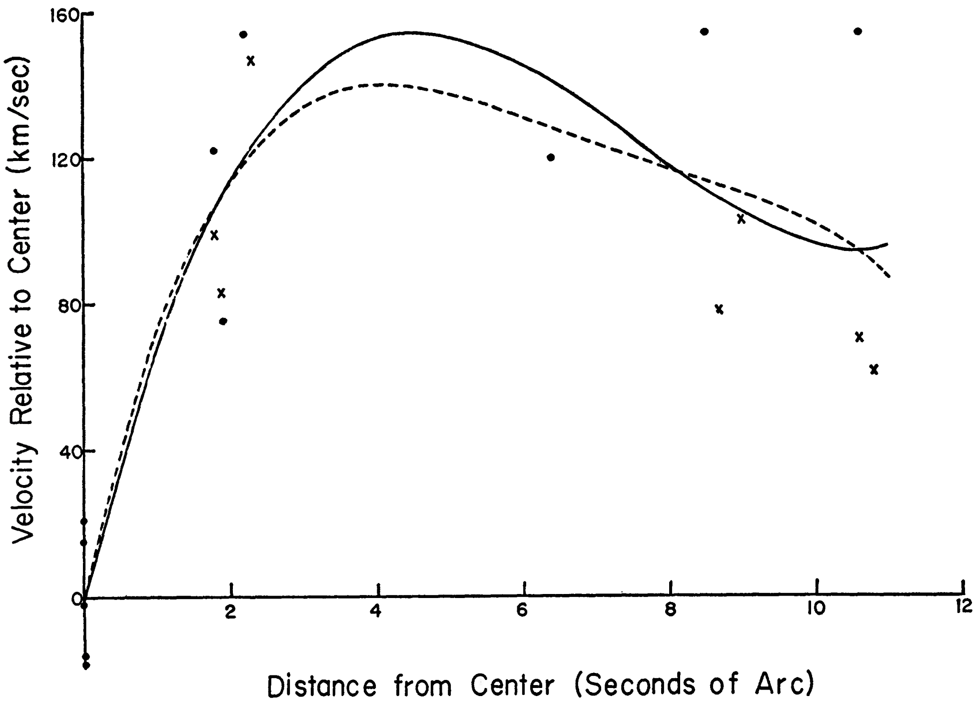

FIG. 3.—Rotation-curve of NGC 7469. Plotted points are velocities from Hα and [N II] λ 6583 emission lines, reflected about center. Dots are from northwest side, crosses from southeast, of center. *Full line:* three-parameter solution; *dashed line:* four-parameter solution.

1. There may be an exceedingly small and bright stellar nucleus in NGC 7469, as has been seen in NGC 4051 and NGC 4151 by Baade and Minkowski and described by Woltjer (1959), and the somewhat different but small nucleus in NGC 1068. However, in all these cases these nuclei have diameters of about 1″, which from the redshifts of the galaxies give diameters of about 70 pc. The distance of NGC 7469 is such that 1″ = 328 pc, so that such a nucleus would have a diameter of only about 0″.2. The nucleus that is made up of stars, producing the continuous spectrum in NGC 7469, has, according to our spectra, a diameter of 1″.4 or less, since its diameter is seeing-limited. This corresponds to a diameter of 460 pc.

2. On the short-exposure spectra the tilted emission lines are seen out to a distance of about 900 pc from the center. Thus the diameter of a fast-rotating region is 1800 pc. The inclined emission lines in NGC 1068 were seen out to a radius of 2000 pc.

3. On the long-exposure spectra the narrow emission lines can be seen intermittently out to a distance of about 3600 pc from the center.

4. NGC 7469 and NGC 1068 are similar, in that they both have a faint outer ring. The diameter of this in NGC 1068 is 30000 pc; in NGC 7469 it is 100″ = 33000 pc. The appearances of these rings are similar, as can be seen by comparison of Figure 1 of this paper with Figure 2 of the paper on NGC 1068, but the ring in NGC 7469 may be the brighter.

From the measured velocities we have deduced that, in its gross character, NGC 7469 is a spiral galaxy with a fairly normal rotation-curve. Though there are uncertainties in

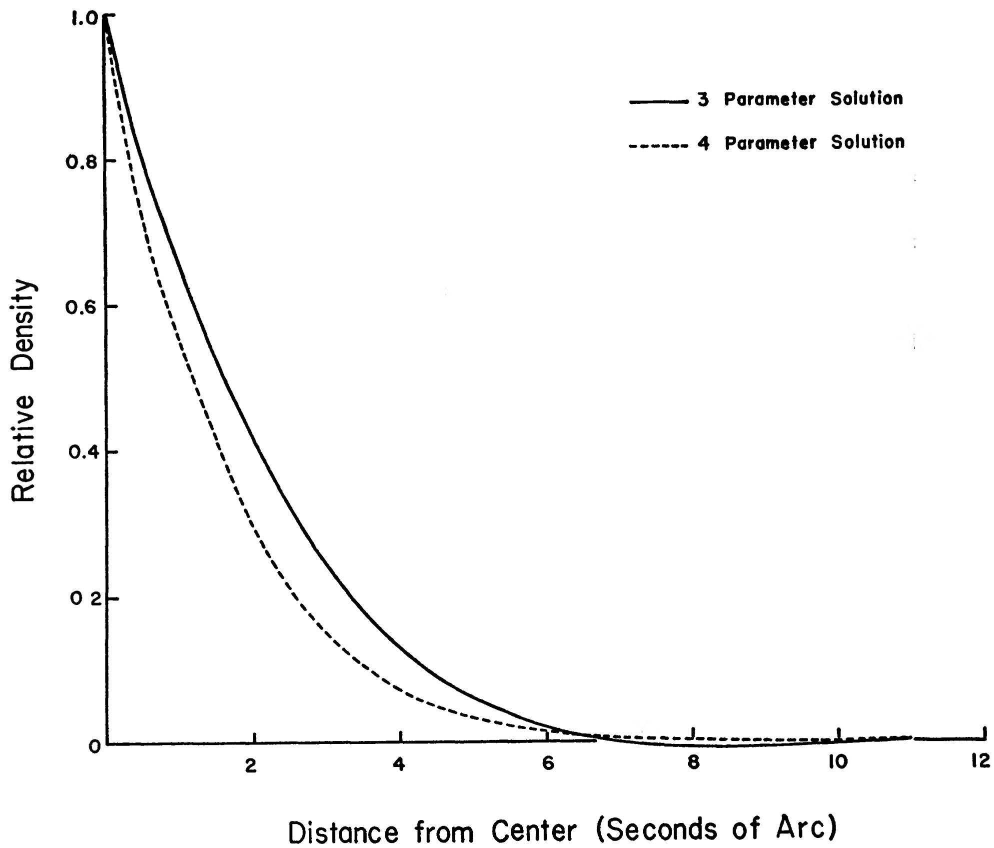

FIG 4—Density in NGC 7469, relative to unit density at center, from three- and four-parameter solution. Note that density runs slightly negative between 7″ and 10″ from center; this is a result of the mathematical nature of the solution and merely indicates that the true density is vanishingly low here.

the form of the rotation-curve and asymmetries may be present, these may be due to the great distance of the galaxy and the consequent difficulty in observing it. We have only been able to obtain the rotation interior to a radius of about 3600 pc. However, the curve appears to have reached a maximum at a distance of about 1 kpc from the center and has flattened off and is beginning to decrease at a distance between 3 and 4 kpc from the center. The mass obtained out to this distance, about $1.1 \times 10^{10} M_{\odot}$, is in reasonably good agreement with corresponding masses in ordinary spirals (Burbidge 1961). In the case of NGC 1068, the mass out to a distance of about 2 kpc was found to be about $2.7 \times 10^{10} M_{\odot}$.

The mass-to-light ratio for that part of NGC 7469 for which we have obtained a mass can be estimated from the apparent magnitude of the nucleus, which was given by

Seyfert as 14.3 (photographic). If this luminosity corresponds to the whole of the mass within 11″ of the center, then $M/L \approx 1$. If, however, the mass of the stars and gas from which this luminosity comes is only that lying within a diameter of 5″.5, then a separate calculation of this mass must be made to derive a more reasonable value for M/L. This can be done by assuming that the central region can be represented by a uniform spheroid with $c/a = \frac{1}{5}$ and $a = 900$ pc. From the observed rotation-curve we put the velocity at the periphery of this spheroid equal to 140 cosec $\xi = 186$ km/sec. Then, since

$$M = \frac{V^2 a}{\alpha G},$$

where $\alpha = 1.8714$ for $c/a = \frac{1}{5}$, we find that $M = 3.9 \times 10^9\ M_\odot$, so that M/L is equal to 0.3. Thus probably M/L lies in the range 0.3–1, which is lower than the values usually found for spirals.

In our analysis of the rotation of NGC 1068 it was shown that the presence of a very high-density nucleus within the volume for which the rotation was obtained—in that case, inside about 800 pc radius—could be excluded. This was done by calculating the effect that such a central "mass point" would have on the rotation-curve where it was observed and showing that it could not be made to agree with the observed curve. In the case of NGC 7469 the same argument holds, and there is no sign that a very dense massive nucleus exists. This does not rule out the possibility that a very small inner nucleus might be present.

To calculate the escape velocity from the center, we consider the central region within a radius of 900 pc to be a uniform spheroid, and then from the calculation above, using the expression given in the analysis of NGC 1068, we find that the escape velocity is 400 km/sec. To obtain the escape velocity directly from the mass distribution corresponding to our full rotation-curve requires a more elaborate calculation, but the value given above is good to within a factor of 2.

On the other hand, the motions of the gas as given by the widths of the wings of Hα are about ± 2500 km/sec; this value is hard to estimate and is rather uncertain. However, it is certainly far in excess of the escape velocity, so that we conclude that gas must be pouring out of the central regions of NGC 7469.

The total energy emitted from the nuclear region amounts to about 4×10^{43} ergs/sec. No estimate is available for the energy emitted in the emission lines, but if we use a value similar to that derived by Seyfert for NGC 1068 (13 per cent), then it must be emitting about 5×10^{42} ergs/sec.

VI. CONCLUSION

There are three separate components in the ionized gas which appear to be present. They are as follows: (1) the gas partaking of the ordered rotational motion of the nuclear region, which is characterized by the comparatively narrow emission lines seen on the short-exposure spectra; (2) the gas with random velocities of order ± 2500 km/sec in the center of the galaxy, which manifests itself in the appearance of the very broad wings of the Hα emission lines; and (3) the lower-density gas showing normal rotational motion in the spiral arms.

The results of the analysis of the rotation are very similar to those which we derived earlier for NGC 1068, and consequently the conclusions that we have drawn from them are very similar. It appears to us that, at least in these two cases and probably in the other Seyfert galaxies as well, we are witnessing a violent event in the evolution of the nuclear regions in which stars are evolving very rapidly, matter is being ejected in large amounts, and the excitation is high as compared with the conditions in normal nuclei. A model of this type was earlier proposed by one of us (Burbidge 1958).

Woltjer (1959) has attempted to estimate the time scale associated with the Seyfert galaxies, on the assumption that this is an evolutionary phase through which all Sa and Sb galaxies pass. From the fact that the Seyfert galaxies have all been classified Sa or Sb and are brighter than $13^{m}.0$, he has concluded that they make up about 4 per cent of the galaxies of this type in the local volume of space which contains the galaxies listed in the Shapley-Ames catalogue. If the characteristic time scale of the Sa and Sb galaxies is $\sim 10^{10}$ years, then it is concluded that the time scale associated with the Seyfert galaxies is a few times 10^{8} years.

There are two basic mechanisms of energy dissipation working in the nuclei. They are the energy loss as determined by the luminosity and that due to mass loss. We plan to discuss these processes in detail in another paper. Suffice it to say here that, while the energy dissipated by radiation in a time scale of the order of 10^{8} years will not begin to exhaust the energy sources in the nucleus, it is the mass loss which, based on the crude estimates that can be made, indicates a time scale very much shorter than 10^{8} years, as Woltjer pointed out. This then suggests that the Seyfert galaxies are much more common, on the basis of the frequencies given above, than they should be. This poses an extremely difficult point. It is possible that an event of the Seyfert type is experienced by *all* spiral galaxies and not only by the Sa and Sb systems. We believe this to be a reasonable assumption, but it has the effect only of reducing the frequency of Seyfert objects among spirals by a factor of 2 or less. Consequently, the difficulty remains.

It is possible that the phenomenon which we are witnessing in a Seyfert galaxy is directly related to the events which give rise to strong non-thermal radio sources associated with galaxies. Though these galaxies are frequently ellipticals, there is some overlap in the spectral characteristics. Thus NGC 1068 and 1275 are both sources of non-thermal radio emission, and many of the galaxies associated with the strong radio sources satisfy criterion ii for the Seyfert galaxies. It also seems probable that these strong radio sources have time scales $\ll 10^{8}$ years (Burbidge 1962).

Most of the observational work described here was carried out at the Lick Observatory, and we wish to thank Dr. A. E. Whitford and other members of the staff (particularly Dr. T. D. Kinman) for the facilities afforded us there. This work was supported in part by a grant from the National Science Foundation.

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