MOTIONS IN BARRED SPIRAL GALAXIES. III. THE ROTATION AND APPROXIMATE MASS OF NGC 3504*

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ABSTRACT

The rotation-curve of NGC 3504 was obtained from measures of the Hα, Hβ, [N II] λ 6583, λ 6548, [O III] λ 5007, [S II] λ 6731, λ 6716 emission lines on spectra taken at the prime focus of the 82-inch telescope and from the Hγ emission line on spectra taken at the Cassegrain focus. The rotation-curve extends out to about 50″ from the center, though there is a gap between about 6″ and 25″ from the center where no emission regions are present. This means that the form of the rotation-curve and hence the mass distribution cannot be very well determined. The rotation-curve in the nuclear region is linear. The orientation of the galaxy has been determined from the shape of the inner bright region in which rotation is seen. The outer arms might suggest that the system is face-on, but the observations of rotation contradict this. These outer arms may be elliptical or not coplanar with the main body. Mass estimates for the nucleus and the whole galaxy have been estimated by making an assumption about the rotation-curve. We conclude that the mass lies in the range $2.5 \times 10^9 M_\odot \ll M \lesssim 9 \times 10^9 M_\odot$. The mass-to-light ratio (photographic) is about 0.7, if a mass of 9×10^9 is assumed. With a mass of $9 \times 10^9 M_\odot$, M/L could be slightly higher than this, since the outer arms were included in the measured luminosity, while no determination of the mass of them can be made.

I. INTRODUCTION AND OBSERVATIONS

NGC 3504 has been classified SBb by Humason, Mayall, and Sandage (1956). A plate obtained at the prime focus of the 82-inch telescope on a baked IIa-O emulsion is shown in Figure 1. Although the galaxy is of small angular extent, it was put on the program for spectroscopic investigation because it appears to contain many H II regions. Actually, the bar is not a well-defined structure, and the galaxy is not a typical barred spiral; we would be inclined to class it as intermediate between a barred and an ordinary spiral. The major axis of the bright main body is about 95″ long. There are two faint outer arms which come from the ends of the major axis and curve around through half a turn so as to form a broken ring. As we shall see later, this structure makes the problem of the orientation of the galaxy in space rather puzzling. The nucleus of the galaxy is very bright and well defined and has a diameter of just over 10″.

Spectra were obtained with the B spectrograph at the prime focus of the 82-inch telescope by the long-slit technique described in earlier papers by us. The slit was aligned along the major axis of the bright main body and perpendicular to it. In galaxies with H II regions the features which are consistently the strongest in the spectral region in which we work are Hα and [N II] λ 6583. In this galaxy, in addition to these lines, it was found possible to measure and use, in constructing the rotation-curve, Hβ, [N II] λ 6548, [O III] λ 5007, and [S II] λ 6716 and λ 6731.

The nucleus is so bright and concentrated that we thought it might be possible to use the greater scale at the Cassegrain focus of the 82-inch telescope (7″.4/mm instead of 25″.4/mm at the prime focus) to get a rotation-curve for this part of the galaxy; this would be an advantage because the prime-focus spectra showed that the rotation across this small nucleus was quite large, and also we would be able to use higher dispersion. Accordingly, spectra were obtained with the Cassegrain spectrograph with quartz prisms and $F/2$ camera (dispersion 170 A/mm at Hγ as compared with a dispersion of about

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330 A/mm at Hα at the prime focus), along and perpendicular to the major axis. The prominent features in these spectra were Hγ in emission and [O II] λ 3726.0 and λ 3728.8. Since the latter was not properly resolved and the two components of the doublet vary in intensity as a function of electron density (cf. Seaton and Osterbrock 1957), which may vary rapidly within the central region of the galaxy, it is not very reliable to use for measures of rotation. Consequently, only velocities derived from the Hγ emission line were used in constructing the rotation-curve.

Six spectra were obtained altogether, at both the prime and the Cassegrain foci, and the dates, position angles, and exposure times are listed in Table 1. All the spectra were measured with the two-co-ordinate measuring machine at the Mount Wilson and Palomar Observatories as described in earlier papers. The velocity of the center of the galaxy was obtained as follows.

Hγ in the Cassegrain spectrum CQ 2/15210, which extended only across the central nucleus, was measured at intervals of 1".2. The spectrum at right angles to the major axis, CQ 2/15211, did not have inclined lines, showing that it was indeed taken perpendicular to the line of nodes. It was a shorter exposure than CQ 2/15210, and only one measure of Hγ, in the center, was made. The mean of the central measure, two on either side

TABLE 1

SPECTRA OF NGC 3504

Number	Date (U.T.)	Exposure (min.)	P.A. of Slit
B 606	1959 Dec. 6	180	152° major axis
B 610	1959 Dec. 7	60	152° major axis
B 611	1960 Feb. 5	30	152° major axis
B 612	1960 Feb. 5	30	62° minor axis
CQ F2/15210	1950 Feb. 13	240	152° major axis
CQ F2/15211	1960 Feb. 13	135	62° minor axis

of the center along the major axis and one perpendicular to the major axis, with equal weight given to each measure, is 1536 km/sec uncorrected for the rotation of our Galaxy.

The two best short-exposure spectra taken at the prime focus are B 610, along the major axis, and B 612, perpendicular to it (which again did not show inclined lines). Three measures, one in the center of the nucleus and one on either side, were made on Hα and [N II] λ 6583 in B 612, and on Hα, Hβ, [N II] λ 6583, λ 6548, and [S II] λ 6716 in B 610; in addition, just one central measure was made on each of [O III] λ 5007 and [S II] λ 6731 in B 610. The mean of all these measures, together with the measures in the two Cassegrain spectra (equal weight for each measure), is 1539 km/sec uncorrected for the rotation of our Galaxy. This value is in good agreement with the mean of the two Cassegrain spectra alone. We therefore took 1539 km/sec to be the uncorrected red-shift velocity of the center of NGC 3504.

For the prime-focus spectra the errors of measurement were investigated in the same way as previously, by measuring the night-sky lines at ten settings across the width of the spectrum. The random errors were of the same order as those found in the observations of the rotations of NGC 7479 and NGC 2903 (Burbidge, Burbidge, and Prendergast, 1960*b*, *c*), i.e., $\pm\frac{1}{3}$ A; there was no trend of residuals across the lines, and this provides a check on the applied curvature correction. There was a small positive systematic error, in that the measured wave lengths of the night-sky lines were slightly larger than the tabular values; the shifts were of the same order as those found in the analyses of NGC 7479 and NGC 2903, i.e., $+\frac{1}{2}$ A. No night-sky features were present on the spectra taken with the Cassegrain camera. However, the good agreement between the red-shift velocities obtained from the prime-focus and Cassegrain spectra suggests that the systematic error lies in the measurement of the night-sky lines themselves.

Our adopted red-shift velocity of 1539 km/sec agrees well with the value given by Humason (Humason *et al.* 1956) of 1513 km/sec. The corresponding values when corrected for galactic rotation are 1485 and 1459 km/sec, respectively. To obtain a distance for NGC 3504, we use our red-shift velocity and a value of the Hubble constant of 75 km/sec per Mpc (Sandage 1958). This gives a distance of 19.8×10^6 pc.

The rotation-curve for NGC 3504 was constructed by subtracting the velocity of the center from all the observed velocities in the spectra taken along the major axis and reflecting the points about the center. The resulting rotation-curve is shown in Figure 2.

II. ANALYSIS OF THE ROTATION-CURVE AND RESULTS

It will be seen from Figure 2 that the rotation-curve can be defined only in two regions. The first is the nucleus, which has a radius of 5″–6″. There is a sharp discontinuity in brightness as measured on a direct plate outside this radius, and the spectra also show that the majority of the emission lines abruptly become too weak to measure outside this radius. A smooth curve which is practically linear has been drawn through the observed points in this region, greater weight being given to the points obtained from the Hγ line, where the scale and dispersion were greater. Outside the nucleus there is a gap extend-

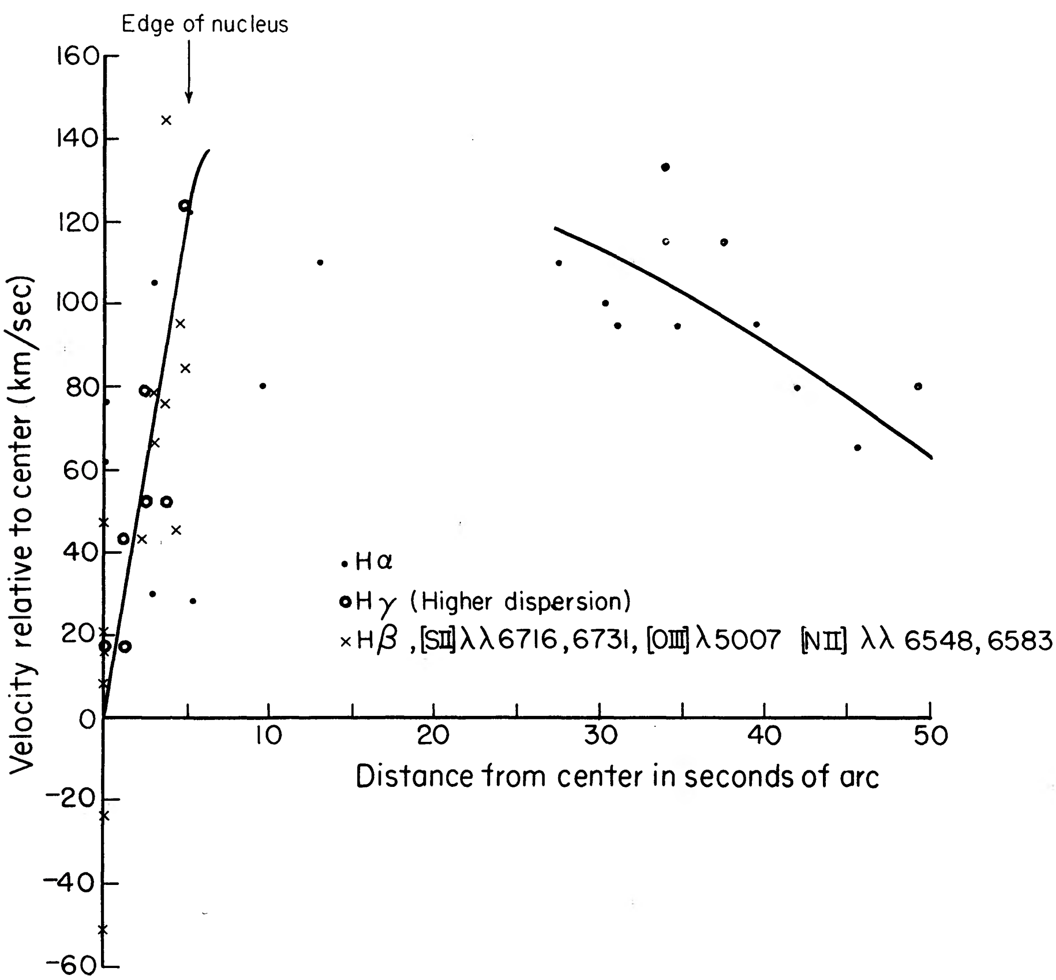

FIG. 2.—Rotation-curve of NGC 3504

ing over about 20″ in which there are no spectral features strong enough to be measured. Between about 25″ and 50″ the rotation-curve can be measured again, and in Figure 2 a freehand curve has been drawn through the observed points.

There appear to be two possible forms that the rotation-curve can have in the gap between about 6″ and 25″ from the center. First, it is certain that the bright nucleus represents a major concentration of mass. This being the case, we should then expect the rotation-curve, just outside the edge of the nucleus, to begin to flatten out and pass through the turnover point. The curve may then drop steeply and rise again, reaching a secondary maximum, and then decline again through the observed points between 25″ and 50″ from the center. Such a curve would be expected if there were two distinct mass distributions—the massive nucleus and a more uniform distribution of mass in the outer parts (cf. the computed curves for two mass distributions in Burbidge *et al.* 1959*a*). Alternatively, we might suppose that after reaching its maximum the curve remains fairly flat for much of the gap between about 6″ and 25″ and then slowly declines, passing through the observed points between 25″ and 50″ from the center.

In view of this uncertainty, clearly the mass distribution or the total mass cannot be determined with much precision. However, we have tried to determine approximate upper and lower limits to the total mass in two ways. A smooth curve has been drawn across the gap between 6″ and 25″ (this curve it not reproduced in Fig. 2) on the assumption that there is *not* a rapid decline and secondary maximum in the gap. A value for the total mass has then been determined from this *assumed* curve. Second, a mass determination has been made for the nucleus, using the observed curve out to 6″. Before we describe the result of these computations, some discussion of the orientation of this galaxy in space will be given in the following paragraphs.

The rather ill-defined bar is aligned along the major axis, along which the slit was set. From the evidence supplied by the two spectra taken perpendicular to the major axis, which showed no tilt in the lines, the direction of the major axis appears to be the direction of the line of nodes (intersection of the plane of the galaxy with the plane of the sky).

If the outer arms are circular, then the galaxy would be approximately face-on, but the observation of quite large rotational velocities and the shape of the bright main body indicate that ξ, the angle between the line of sight and the normal to the plane of the galaxy, is reasonably large. Thus the contour defined by the outer arms, if they are coplanar with the equatorial plane of the main body, must be elliptical, and we see them foreshortened until they are roughly circular. Alternatively, they may not be co-planar with the main body.

In determining the orientation, we *assume* that the bright main body is circular in the plane of the galaxy; the observed ratio of its major to minor axis then gives $\xi = 60°$. In this case the true rotational velocity, V, is related to the observed rotational velocity, U, by the relation

$$V = U \operatorname{cosec} \xi ,$$

and consequently the mass determined from the observed rotation-curve must be corrected by multiplying by $\operatorname{cosec}^2 \xi$.

We now return to the mass determination. An estimate was first made by using a smooth curve joining the two parts of the curve shown in Figure 2. This rotation-curve was analyzed by the method described in previous papers (Burbidge *et al.* 1959*b*, 1960*a*, *c*). If $\rho(a)$ is the density of a spheroidal shell of semimajor axis a and eccentricity $k = (a^2 - c^2)^{1/2}/a$, then the measured rotational velocity $U(\varpi)$, where ϖ is the distance from the center, is related to the density distribution through the integral equation

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

This equation is solved by substituting Taylor expansions for $U(\varpi)$ and $\rho(a)$ and equating powers of ϖ.

In this case a five-term expansion for U was used. Integration of the expression thus obtained for the density gives the total mass interior to the last observed point on the rotation-curve. For this calculation it was assumed that $c/a = \frac{1}{8}$, and that $a = 50'' = 4800$ pc, using the distance derived in Section I. The total mass obtained in this way was $M = 7 \times 10^9\ M_\odot$. When this is corrected by multiplying by ($\text{cosec}^2\ \xi$), we find that

$$M = 9 \times 10^9\ M_\odot .$$

Next we can determine the mass of the nucleus out to about 6″ from the center. We suppose that the nucleus can be represented by a single spheroid of uniform density. This is compatible with the linear form of the rotation-curve in this region. It was shown in an earlier paper (Burbidge *et al.* 1959*a*) that in this case the total mass of the nucleus M_N, is given by

$$M_N = \frac{a U^2}{G \alpha} \text{cosec}^2 \xi , \qquad (2)$$

where a is the semimajor axis of the nucleus; U is the observed velocity at the periphery of the nucleus; ξ has been defined previously; and

$$\alpha = \frac{3}{2} \frac{a^2}{a^2 - c^2} \left[\frac{a}{(a^2 - c^2)^{1/2}} \cos^{-1} \left(\frac{c}{a} \right) - \frac{c}{a} \right] .$$

We can expect the nucleus to be far more nearly spherical than the outer parts of the galaxy. Consequently, we have put $c/a = \frac{1}{2}$, so that $\alpha = 1.418$. From Figure 2 we see that $U \simeq 140$ km/sec and $a = 6'' = 576$ pc, by using the distance derived in Section I. If we substitute these values in equation (2), we obtain

$$M_N = 2.5 \times 10^9\ M_\odot .$$

If this is the whole of the mass of the galaxy, then it is a simple matter to calculate that at a distance $50'' = 4800$ pc from the center the rotational velocity would be 31 km/sec relative to the center, whereas from Figure 2 we see that it is about 65 km/sec. This clearly shows that there is a considerable amount of mass outside the nucleus. If, on the other hand, the rotation-curve does fall steeply outside the nucleus and then rises again, reaching a secondary maximum before passing through the observed points between 25″ and 50″ from the center, the mass estimate obtained on the basis that there is a smooth rotation-curve from 0″ to 50″, with a single maximum, will be too high.

We conclude, therefore, that $2.5 \times 10^9\ M_\odot \ll M \lesssim 9 \times 10^9\ M_\odot$. The apparent photographic magnitude of NGC 3504 is 11.6 (Humason *et al.* 1956). If we use the distance of 19.8×10^6 pc, then we find that, using a mass of $9 \times 10^9\ M_\odot$, M/L (photographic) = 0.7. However, the apparent photographic magnitude given by Humason *et al.* was based on measurements made by Pettit (1954), taken through diaphragms of 4 and 5 minutes of arc. This means that the outer broken ring in NGC 3504 was included in the total luminosity. On the other hand, in determining the mass we have not been able to take into account the mass of the outer ring. We have no way at all of estimating this, but clearly it has some mass and hence the true mass-to-light ratio must be greater than 0.7. However, it is difficult to see how the mass-to-light ratio could be increased to many times the value derived.

The nucleus of NGC 3504 is clearly different in stellar population from the usual nuclei of Sb galaxies. The great strength and number of the emission lines shows that there must be stars of high luminosity and temperature in the nucleus. The low mass-to-light ratio also points in this direction.

Finally, it is worth emphasizing that this investigation of NGC 3504 has shown that it is not always safe to discuss the geometry and orientation in space of a galaxy without first studying it spectroscopically with the slit set in various orientations. A cursory glance at NGC 3504, with its circular, outer arms, would have suggested that it might be nearly face-on.

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