THE ASTROPHYSICAL JOURNAL, 239:50–53, 1980 July 1

ROTATION AND MASS OF THE INNER 5 KILOPARSECS OF THE S0 GALAXY NGC 3115

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Received 1979 September 17; accepted 1980 January 9

ABSTRACT

NGC 3115 is an isolated field galaxy of type S0. It has a small disk embedded in a large flattened halo. Observed velocities rise steeply to 200 km s^{-1} at $r = 450$ pc and then are flat at $V = 267$ km s^{-1} from $r = 700$ to $r = 4.7$ kpc. Based on a simple spheroid model, the mass is greater than $7 \times 10^{10}\ M_\odot$ interior to $r = 5$ kpc. By its kinematic properties, NGC 3115 resembles a rapidly rotating high-density disk galaxy rather than a slowly rotating elliptical galaxy. There is no evidence for a variation in $(M/L)_B$ from 1 to 5 kpc.

Subject headings: galaxies: individual — galaxies: internal motions

I. INTRODUCTION

During the past few years, new observations of the rotational velocities of both spiral and elliptical galaxies have altered our ideas of the kinematics and dynamics of galaxies. For spirals, extended rotation curves in both the optical (Rubin, Ford, and Thonnard 1978; Rubin, Ford, and Thonnard 1980) and radio regions (Bosma 1978; Krumm and Salpeter 1977) have shown that rotation curves are flat to large distances from the nucleus. Mass distributions in disk galaxies are significantly more extended than had been assumed. For ellipticals, optical observations (Bertola and Capaccioli 1975; Illingworth 1977) indicate that most elliptical galaxies are rotating only slightly. Their morphological figures are apparently not flattened by rotation and the true shapes may be triaxial ellipsoids (Binney 1978; Miller and Smith 1979). For S0 galaxies, few observations exist and dynamics are not yet clear. Therefore, we are presenting our spectroscopic observations of the S0 galaxy NGC 3115, a galaxy whose rotational properties clearly place it with the disk galaxies.

The first study of the rotation of NGC 3115 was made by Humason in 1936 (Oort 1940; Zwicky 1957). Subsequent observations were published by Minkowski (1960) and Morton and Chevalier (1973). Williams (1975) showed that the major axis rotation curve rises to 260 km s^{-1} at a radius of 25″ from the nucleus and remains constant out to 100″. Our new data, which confirm Williams's results, have higher spatial resolution and significantly smaller statistical errors.

Although older classifications have considered the galaxy as a transition between an E7 and an S0 type, the presence of a distinct disk together with the rotational properties identify NGC 3115 as an S0 halo plus disk system. The luminosity structure of the galaxy has been studied by numerous authors, most recently by Strom *et al.* (1977) who were able to trace the halo out to a radius of 30 kpc. We will use their photometric data as the basis of a discussion of the mass-luminosity properties below. The galaxy is not featureless, but shows luminosity discontinuities along the major axis, as if dust lanes or incipient structure were viewed edge-on. This structure is visible on a plate of NGC 3115 taken at the prime focus of the Kitt Peak 4 m telescope by S. Strom and reproduced in Figure 1 (Plate 1). On longer exposures (Strom *et al.* 1977) the disk disappears in an extensive halo which covers most of the field of this print.

The systemic velocity of NGC 3115 is too small to obtain a reliable distance estimate through application of the Hubble law. Neither can we obtain a distance through group membership, for NGC 3115 is an isolated field galaxy (Materne 1978; Kraan-Korteweg and Tammann 1979). We adopt a distance of 10 Mpc, the distance estimated by Strom *et al.* (1977) through comparison of the luminosity function of the globular clusters in NGC 3115 and in M 31.

II. OBSERVATIONS

On 3 February 1976 we took two spectrograms along the major axis (P.A. = 44°) of NGC 3115, with the KPNO 4 m RC spectrograph. They were taken with the Carnegie image tube (RCA C33063) in the blue spectral region at a dispersion of 50 Å mm^{-1}; exposure times were 38 and 157 minutes on N_2 baked IIIa-J plates with the transfer optics stopped down to f/2. The Moon, three days past new, was well below the horizon during the exposures. The plates are of high quality, and a reproduction of the longer exposure is shown in Figure 1. The slit width was 1″.3 and the slit

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TABLE 1

ADOPTED WAVELENGTHS FOR MEASURED ABSORPTION LINES

Identification	λ_{lab} (A)	$\lambda_{adopted}$ (A)	Identification	λ_{lab} (A)	$\lambda_{adopted}$ (A)
Ca II	3933.664	3933.2	Hγ	4340.470	4339.6
Ca II	3968.470	3967.9	Fe I	4383.548	4383.7
Mn I	4033.000	4032.7	Cr I	4666.001	4666.6
Fe I	4045.815	4045.8	Hβ	4861.332	4861.1
Ca I	4226.728	4226.5	Fe I	4920.510	4920.1
Fe I	4271.765	4273.0	Fe I	5041.760	5041.2
Fe I	4325.766	4325.4	Mg I	5183.614	5186.0

length was 5′. The major axis diameter out to 25 mag arcsec^{-2} is 8′.3 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). Velocities have been measured out to a diameter of 200″ or 40% of d_{25}. Because more detailed studies are presently underway (G. Illingworth, private communication; L. Searle and J. Rose, private communications) we have no plans to continue our observations and hence are reporting the present limited results. Earlier abstracts of this work have appeared (Rubin, Peterson, and Ford 1976; Ford, Peterson, and Rubin 1976).

Fourteen absorption lines were measured for velocities; the lines are identified in Figure 1 by their laboratory wavelengths and listed in Table 1. The plates were measured with a Mann two-dimensional measuring engine with a conventional microscope and reduced with standard procedures which correct for curvature. The resolution of the absorption lines is sufficiently high that no problems were encountered in using this technique. We believe that there has been no loss of accuracy in not using the recent technique of cross-correlation of digital data.

We determine a heliocentric systemic velocity of $V_H = 662$ km s^{-1} from a mean of all velocities from all absorption lines. However, velocities determined from different absorption lines show systematic differences which we attribute to small differences between the laboratory wavelengths and the effective wavelengths of the features in the galaxy spectrum. The differences are primarily the result of line blends and the intensity variation of the continuum. Accordingly, to bring the velocities of all lines into coincidence, new wavelengths were adopted for each line; the adopted wavelengths are listed in Table 1. The central velocity found here has no validity independent of the adopted wavelengths and we therefore assign no error to the central velocity. Velocities with respect to the nucleus, however, are independent of the adopted wavelengths. At least 10 prior determinations of the systemic velocity exist, ranging from $V_H = 591$ km s^{-1} $\pm$ 40 (Mayall and de Vaucouleurs 1962) to $V_H = 728 \pm 9$ km s^{-1} (Williams 1975).

From the measured velocities, mean velocities as a function of distance from the nucleus were determined for each 5″ interval. These are plotted in Figure 2 and listed in Table 2. Even though the principal plane of NGC 3115 is very close to 90° to the line of sight, a correction is necessary to convert velocities on the plane of the sky to rotational velocities in the galaxy, because each line profile is an integration along the line of sight through the galaxy. Models incorporating these projection effects for M31 (Rubin, Ford, and Kumar 1973) and M32 (Peterson and Baumgart, unpublished) suggest that the center of gravity of the line profile will be lower than the true rotational velocity by about 10–20%. We have not corrected the observed velocities in NGC 3115 for this; both the mass and the mass-luminosity ratio discussed below are thus lower limits.

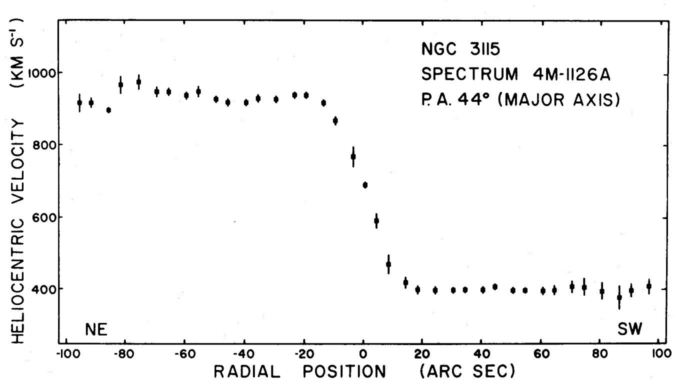

FIG. 2.—Heliocentric line-of-sight velocity as a function of distance from nucleus for NGC 3115. Each plotted point is the mean of all velocities measured from 14 absorption lines within 5″ bin; error bars signify 1 σ mean error.

TABLE 2

MEAN HELIOCENTRIC VELOCITIES AS A FUNCTION OF RADIUS FOR NGC 3115

R (arc sec on sky)	No. of measures in mean	V ± σ (km/s)	|V-662| (km/s)	R (arc sec on sky)	No. of measures in mean	V ± σ (km/s)	|V-662| (km/s)
0	2	685± 6	23				
NE - 3.8	4	766±28	104	SW + 3.8	4	583±21	79
- 9.1	9	866±12	204	+ 9.2	10	463±26	199
-14.1	19	916± 9	254	+14.1	17	415±16	247
-19.3	21	931± 9	269	+19.4	23	396±12	266
-24.4	27	935± 9	273	+24.3	26	394±11	268
-29.5	28	923±10	261	+29.5	27	389± 9	273
-34.6	28	923±10	261	+34.7	28	390± 7	274
-39.8	28	915±10	253	+39.8	28	390± 7	272
-44.9	28	914± 9	252	+44.9	28	398± 9	264
-50.0	27	921±10	259	+50.0	27	394± 8	268
-54.9	21	937±15	275	+55.0	25	394± 8	268
-59.9	18	931±11	269	+60.0	20	392±11	270
-65.0	15	938±11	276	+65.1	20	393±13	269
-70.3	11	938±15	276	+70.3	18	402±17	260
-75.5	8	971±21	309	+75.4	18	400±24	262
-80.6	8	967±23	305	+80.4	14	394±23	265
-85.7	6	894± 8	232	+85.5	10	376±33	286
-90.8	6	912±14	250	+90.9	4	391±17	271
-95.6	3	910±26	248	+96.0	4	401±21	261

The observed velocities rise from $V = 100$ km s^{-1} at 4″ (200 pc) to 200 km s^{-1} at 9″ (450 pc) and are flat thereafter at $V = 267$ km s^{-1} from 14″ to 95″ (700 pc to 4.7 kpc). This flat rotation curve with its high V_{max} is characteristic of big-bulge spirals, i.e., Sa's. Maximum rotational velocities for Sa galaxies range from 250 km s^{-1} to 400 km s^{-1} (Rubin, Ford, Thonnard 1980); V_{max} for NGC 3115 is at the low end of this range. The steep central gradient implies a very high central density ($\sim V^2/R^2$), high even with respect to central densities for Sa galaxies. Thus the kinematical properties of NGC 3115 clearly place it with the rapidly rotating disk galaxies rather than the slowly rotating elliptical galaxies.

III. DISCUSSION

To discuss adequately the mass distribution in NGC 3115, we need an understanding of the disk and bulge components of the mass, knowledge of the velocity dispersion as a function of distance from the nucleus, and rotational velocities away from the major axis (e.g., Oort 1964; Bertola and Capaccioli 1975). Lacking these data, we take the following simple approach. We assume that the mass is distributed in homogeneous spheroids of uniform axial ratio ($b/a = 0.4$; Strom *et al.* 1977) with a density at r given by

$$\rho(r) = \rho_0/[1 + (r/x)^n] .$$

We then search for values of the central density, ρ_0, the core radius x, and the exponent n which will reproduce the observed velocities. This procedure uses the motions of the disk stars as test particles in the total gravitational mass out to the limit of our observations. The model which adequately fits the observations (Fig. 3) has $\rho_0 = 9 \times 10^{10}\ M_\odot$ kpc^{-3}, $x = 0.2$ kpc, and $n = 2.1$. In this model the rotational velocity is 270 km s^{-1} beyond $r = 1$ kpc. Interior to this radius, the model rotation curve lies slightly above the observed rotation curve. We do not consider this a problem, because in the real galaxy the mean tangential velocities would be lower than the circular velocities, for random velocities play a significant role in the dynamical balance against the inward pull of gravity. Exterior to 1 kpc, the velocity dispersion has decreased to < 180 km s^{-1} from its nuclear value of 200–300 km s^{-1} (Morton and Chevalier 1973; Faber and Jackson 1976). Thus beyond 1 kpc the rotation dominates, for the ratio of rotation velocity to velocity dispersion is greater than 1.5.

Some features of this simple model are illustrated in Figure 3. The bottom plot is a comparison of the model rotation curve (*solid curve*) and the observed velocities. The effect on the rotation of adding a nuclear mass of $10^9\ M_\odot$ is shown by the dashed line. In the central figure we show the integrated mass as a function of radius. A mass of greater than $7 \times 10^{10}\ M_\odot$ is located interior to $r = 5$ kpc.

For the adopted spheroid model, we can predict the mass surface density in the equatorial plane, as viewed on the sky, i.e., for $i = 90°$. The variation of the surface density with r (Fig. 3, *upper curve*) comes from an integration along the line of sight of the spatial density. If the ratio of mass to luminosity is constant, 1 kpc $< r < 5$ kpc, then the variation of major axis luminosity will show a parallel trend with r; if however M/L changes substantially over this range in r, then the mass density curve and the luminosity profile should have different slopes. Interior to $r = 1$ kpc, our dynamical model is too approximate to be of use. In the upper part of Figure 3 we plot the major axis photoelectric photometry of Strom *et al.* (1977), r

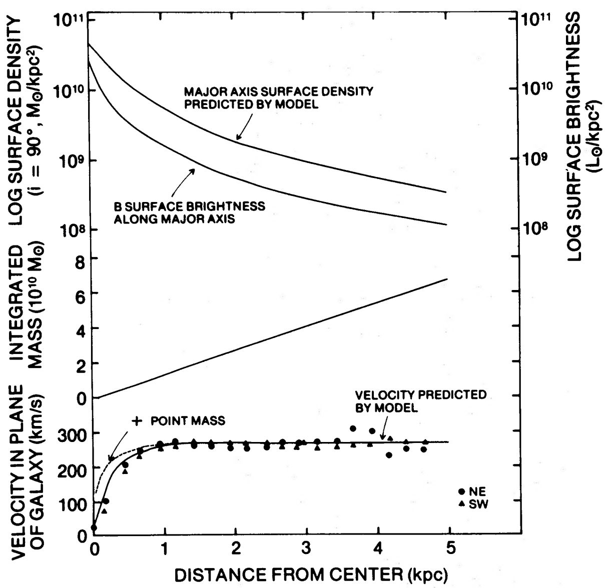

FIG. 3.—*Bottom*: mean observed velocities out to $r = 5$ kpc as a function of distance superposed upon the rotation curve predicted by spheroid model described in text. *Middle*: integrated mass as a function of distance from center. *Upper*: variation of the major axis surface density as a function of distance from the center, as predicted by spheroid model. Below it is plotted the variation of B surface brightness, $r > 1$ kpc (Strom *et al.* 1977), joined to the plot of variation of photographic surface brightness, $r < 1$ kpc (van Houten 1961). The similarity of slopes, $r > 1$ kpc, indicates that $(M/L)_B$ is constant in this distance range.

> 1 kpc, as a function of r. For $r < 1$ kpc, we have matched the photographic reductions of van Houten (1961) to the Strom curve. For small r, the van Houten work is preferable, for it was determined with a smaller scanning aperture (2.″6) than the 30.″3 diaphragm used in the photoelectric observations. The luminosity has been corrected for $0^{m}.1$ extinction ($b = +36.°8$). The similarity in the slope of the predicted surface density with that of the observed luminosity suggests that the blue mass-to-luminosity ratio is essentially constant between 1 and 5 kpc. The overall mass of the galaxy is dominated by the bulge halo; hence a single spheroid model predicts the projected mass surface density reasonably well. Along the major axis the disk contribution to the luminous surface density is significant, of the order of one-half the light, but its contribution is diluted by the 30″ scanning aperture. Furthermore, the major and minor axis luminosity profiles are sufficiently similar so that the conclusion regarding the constancy of M/L should be valid.

We summarize the conclusions of this study as follows: NGC 3115 is an isolated field galaxy, of type S0. It has a small disk embedded within a large flattened halo. Kinematically, the galaxy exhibits a flat rotation curve with high V_{max}. Similar rotation curves are observed in large bulge disk galaxies, but not in most ellipticals. The mass is at least $7 \times 10^{10}\ M_{\odot}$ within $r = 5$ kpc (40% of r_{25}). A simple mass model suggests that the mass-to-luminosity ratio is constant from 1 to 5 kpc from the nucleus.

We thank the director of the Kitt Peak National Observatory for making telescope time available, and Dr. Steve Strom for supplying the print of NGC 3115.

REFERENCES

Bertola, F., and Capaccioli, M. 1975, *Ap. J.*, **200**, 439.
Binney, J. 1978, *M.N.R.A.S.*, **183**, 501.
Bosma, A. 1978, Ph.D. thesis, University of Groningen.
de Vaucouleurs, G., de Vaucouleurs, A., and Cowin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).
Faber, S. M., and Jackson, R. E. 1976, *Ap. J.*, **204**, 668.
Ford, W. K., Jr., Peterson, C. J., and Rubin, V. C. 1976, *Carnegie Institution Year Book 75* (Washington, D.C.: Carnegie Institution of Washington) p. 124.
Illingworth, G. 1977, *Ap. J.* (*Letters*), **218**, L43.
Kraan-Korteweg, R. C., and Tammann, G. A. 1979, preprint.
Krumm, N., and Salpeter, 1977, *Astr. Ap.*, **56**, 465.
Materne, J. 1978, preprint.
Mayall, N. U., and de Vaucouleurs, A. 1962, *A.J.*, **67**, 363.
Miller, R. H., and Smith, B. F., 1979, *Ap. J.*, **227**, 785.
Minkowski, R. 1960, *Ann. d'Ap.*, **23**, 385.
Morton, D. C., and Chevalier, R. A. 1973, *Ap. J.*, **179**, 55.
Oort, J. H. 1940, *Ap. J.*, **91**, 273.
———. 1964, in *Stars and Stellar Systems*, Vol. **5**, *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 455.
Rubin, V. C., Ford, W. K., Jr., and Kumar, C. K. 1973, *Ap. J.*, **181**, 61.
Rubin, V. C., Ford, W. K., Jr., and Thonnard, N. 1978, *Ap. J.* (*Letters*), **225**, L107.
Rubin, V. C., Ford, W. K., Jr., and Thonnard, N. 1980, in preparation.
Rubin, V. C., Peterson, C. J., and Ford, W. K., Jr. 1976, *Bull. A.A.S.*, **8**, 297.
Strom, K. M., Strom, S. E., Jensen, E. B., Moller, J., Thompson, L. A., and Thuan, T. X. 1977, *Ap. J.*, **212**, 335.
van Houten, C. J. 1961, *Bull. Astr. Inst. Netherlands*, **16**, 1.
Williams, T. 1975, *Ap. J.*, **199**, 586.
Zwicky, F. 1957, *Morphological Astronomy* (Berlin: Springer-Verlag), p. 212.

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FIG. 1.—*Left*: NGC 3115, from a 4 m plate taken by S. Strom, showing luminosity structure in disk. Print is to same scale as spectrum, NE is up. *Right*: KPNO 4 m image tube spectrum of NGC 3115 with slit along disk; original dispersion 50 Å mm^{-1}, exposure time 157 minutes. Velocities have been measured from 14 absorption lines indicated to a maximum extent of 96″.

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