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DYNAMICS OF EARLY-TYPE GALAXIES. II. THE ROTATION CURVE OF THE S0 GALAXY NGC 128

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ABSTRACT

In this paper we study the rotation curve of the peculiar S0 galaxy NGC 128. Complementary information on the morphology of the object and its group, and a photometric investigation, are also presented. The rotation curve has been obtained by measuring the H and K absorption lines up to 40″ (12 kpc, assuming a distance of 60 Mpc) from the nucleus on spectra taken with the 200 inch (5.1 m) telescope. This curve shows a flat maximum at a level of 200 km s^{-1}. A central gradient of 40 km s^{-1} $arcsec^{-1}$ has been measured on a 4 m KPNO spectrum. The mass within 40″ from the nucleus is estimated to be $M = 1.4\ 10^{11}\ M_{\odot}$, and the corresponding mass-to-light ratio $M/L_B = 7$.

Subject headings: galaxies: individual — galaxies: internal motions

I. INTRODUCTION

In a previous paper (Bertola and Capaccioli 1975, hereafter Paper I) we presented a study of the elliptical galaxy NGC 4697. In the present paper, which is the second of this series, we deal with the lenticular galaxy NGC 128. This object, classified $S0_1$ pec by Sandage (1961) and S0 pec by de Vaucouleurs (1963), has been selected for this program because of its brightness and size, both well suited for the long slit spectroscopic technique.

In the following two sections, an account will be given of morphological and photometric properties. Section IV will deal with the spectroscopic observations and their reductions. The data will be discussed in the last section.

II. MORPHOLOGY OF NGC 128 AND ITS GROUP

The lenticular NGC 128 is the dominant member of a group of galaxies (Fig. 1) which has been located by Zwicky, Karpowicz, and Kowal (1965) at the edge of the "near" "open"[1] cluster No. 8 of field 383. Four other members, qualified on the basis of their redshifts, are NGC 126, 127, and 130, and an anonymous faint galaxy 5′.6 north, 9′.5 preceding NGC 128. The membership of NGC 125, a peculiar galaxy in the same area, is controversial, since its recession velocity exceeds the mean of the others by 1000 km s^{-1}.

A morphological classification of the group members is given in Table 1. For nonclassified objects it is based on a glass copy of Palomar plate PH 771 kindly made available to us by A. Sandage. We notice that in the group all the galaxies are within late E and early S types. In the same table we list the individual recession velocities from different sources. With these data, using a Hubble constant of 75 km s^{-1} Mpc^{-1}, we find that the distance of the group is 60 Mpc, a value which will be used in the following.

In order to extend the morphological investigation to the outermost regions of NGC 128 and to the group, two deep plates (IIIa-J baked and W2c) of the NGC 128 field were obtained with the 48 inch (1.2 m) Palomar Schmidt telescope (Fig. 1). Tracings of these plates with a Joyce-Loebel microdensitracer reveal the rather large extension of NGC 128, which along the

[1] Zwicky's terms.

TABLE 1

NGC 128 GROUP: RECESSION VELOCITIES CORRECTED FOR GALACTIC ROTATION (km s^{-1})

Object and Type*	Humason *et al.* (1956)	Hodge and Merchant (1966)	Present Paper†	Mean
Anon $00^h26^m.1 + 02°40'$, Sa.......	4594 ± 50	...	...	4594
NGC 125, S0 pec................	5423 ± 50	...	...	5423
NGC 126, E/SB0................	...	4392 ± 50	...	4392
NGC 127, Sa...................	4228 ± 40	...	4186 ± 30	4207
NGC 128, S0 pec................	4384 ± 50	...	4383 ± 50	4384
NGC 130, E5...................	...	4657 ± 70	4566 ± 50	4612
Mean (including NGC 125)....	...	...	...	4602
Mean (excluding NGC 125)....	...	...	...	4438

* Morphological classification from present paper photographic material.

† Redshifts have been measured on Ca II doublet and, for NGC 127, on [O II] 3727–3729 lines.

major axis reaches 4′.5 (78 kpc). This large envelope appears to protrude southward in the form of filaments going to NGC 126. A bridge also connects NGC 127, as described by Burbidge and Burbidge (1959) and Sandage (1961). Another interesting feature disclosed by this deep photographic material is the ring around NGC 125. It is asymmetrically placed with respect to the nucleus and has a diameter of at least 70 kpc.

As an individual galaxy, NGC 128 has attracted the attention of several investigators because of its peculiar appearance. In fact, both its components, the central bulge and the flat disk, exhibit remarkable shapes and properties. The bulge, on medium exposures, appears squared by four symmetric bumps giving rise to the characteristic box shape noticed by Burbidge and Burbidge (1959) and shown by Sandage (1961) in the Hubble Atlas. In this connection, it is interesting to note that de Vaucouleurs (1974) has recently pointed out that the so-called *box-shaped* or *peanut-shaped* nucleus is a property common to several galaxies seen edge-on.

A second peculiarity of NGC 128, first mentioned by Burbidge and Burbidge (1959), is the apparent bending toward the west of the principal plane of the galaxy. On our isophotal maps the phenomenon is seen to be more complex, since the outermost ends of the disk appear bent in the opposite direction, toward the east.

III. PHOTOMETRIC PROPERTIES OF NGC 128

Our photometric study of NGC 128 is based on three calibrated plates (103a-O and GG13 filter) taken at the Newtonian focus of the Asiago 122 cm reflector. The reduction procedure is the same as in Paper I. The zero point of our photometric scale is the sky brightness. It was determined by means of two photoelectric observations given by de Vaucouleurs and de Vaucouleurs (1972) and has the value $\mu_{\text{sky}} = 21.23$ mag arcsec^{-2}. The luminosity profiles along the estimated major (P.A. 0°) and minor (P.A. 90°) axes together with the ellipticity curve are given in Table 2 and represented in Figure 2. Hodge and Merchant (1966) published surface photometric data for the triplet of galaxies NGC 127, 128, and 130, mainly in the *V*-band. In the region where the *B* color is available (down to $\mu_B = 24$ mag arcsec^{-2}) there is a substantially good agreement with our results, with two major disagreements. In fact our luminosity profile along the major axis is more peaked toward the center and more symmetric in the two sides, as clearly visible in Figure 2. Moreover, the northern side exhibits a shoulder at

TABLE 2

NGC 128: LUMINOSITY PROFILES AND LIGHT DENSITY

Log $I(x)$*	x (arcsec) South	North	West	East	ϵ	r (arcsec)	Log ψ†
+1.0:........	0.0	0.0	0.0	0.0	...	1	+0.17
+0.5........	5.7	5.7	3.5	3.8	0.36	2	−0.08
+0.4........	7.2	7.0	4.3	4.7	0.37	4	−0.45
+0.3........	9.0	8.7	5.1	5.5	0.40	6	−0.76
+0.2........	10.8	10.5	5.9	6.5	0.42	8	−1.01
+0.1........	13.0	12.5	6.7	7.3	0.45	10	−1.22
+0.0........	15.2	15.2	7.5	8.3	0.48	12	−1.40
−0.1........	18.1	18.5	8.3	9.0	0.53	14	−1.54
−0.2........	23.3	22.0	9.1	9.9	0.58	16	−1.65
−0.3........	28.5	26.5	10.0	10.8	0.62	18	−1.75
−0.4........	32.5	29.5	10.8	11.7	0.64	20	−1.83
−0.5........	37.0	33.5	11.6	12.5	0.66	25	−2.01
−0.6........	40.0	38.5	12.5	13.5	0.67	30	−2.17
−0.7........	43.2	48.0	13.4	14.5	0.69	35	−2.33
−0.8........	47.0	60.0	14.5	15.8	0.72	40	−2.48
−0.9........	50.0	65.5	15.4	17.5	0.72	45	−2.62
−1.0‡.......	52.5	68.0	16.5	19.0	0.71	50	−2.77
−1.1........	54.0	70.0	17.5	20.0	0.70	55	−2.91
−1.2........	55.0	71.5	18.5	20.8	0.69	60	−3.05
−1.3........	56.3	73.0	19.5	21.3	0.68	65	−3.18
−1.4........	57.5	75.0	20.5	22.0	0.68	70	−3.32
−1.5........	66.0	77.5	21.5	22.8	0.69	75	−3.46
−1.6........	74.0	82.2	22.7	23.3	0.71	80	−3.59
−1.7........	77.0	89.0	23.8	24.0	0.71	85	−3.73
−1.8........	79.0	96.0	24.8	24.5	0.72	90	−3.86
−1.9........	81.0	102.5	25.9	25.1	0.72	95	−4.00
−2.0........	83.0	109.0	26.9	25.8	0.73	100	−4.13

* Log $I = 0$ corresponds to $\mu_B = 21.23$ mag arcsec^{-2}.

† Assuming that NGC 128 is an edge-on galaxy at a distance of 60 Mpc, the light density ψ is given in units of 0.73 $L_\odot$ pc^{-3}.

‡ Below this level all values have been measured on one plate.

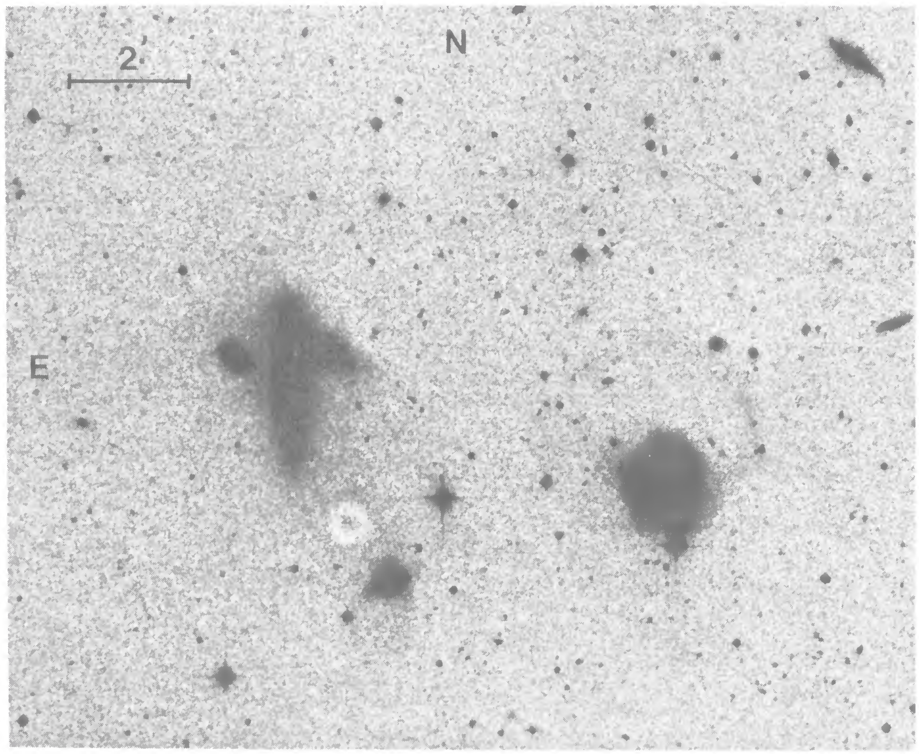

FIG. 1.—Reproduction of the 48 inch (1.2 m) IIIa-J plate PS 4178 of NGC 128 group. The bridges connecting NGC 128 (bright galaxy at left) to NGC 126 and 127 are visible, as well as the large asymmetric ring around NGC 125. The white spot between NGC 126 and 128 is a plate defect.

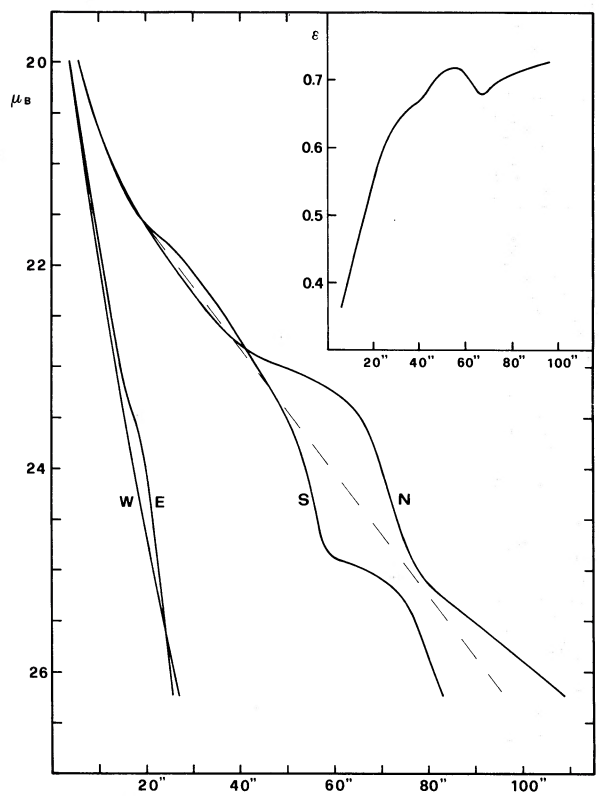

FIG. 2.—Luminosity profiles along major (P.A. 0°) and minor (P.A. 90°) axes of NGC 128. The dashed line is a double exponential representation of the mean of the two sides of the luminosity profile along the major axis. *Inset:* Ellipticity curve.

about 60″ from center, at the same position where the bridge connecting NGC 127 to NGC 128 crosses the latter. At the same distance Hodge and Merchant find a dip of luminosity on both sides.

In order to compare NGC 128 with the other giant galaxies, we should give the total absolute magnitude. Unfortunately, the closeness and the interactions with other faint companions, entangling the outer isophotes of NGC 128, make it difficult to carry out a precise surface integration to derive the total apparent magnitude. Taking into account both the presence of the nearby companions and the contribution of the outer envelope from our photometry we estimate that the total magnitude is 0.4 mag brighter than the value B = 13.01 mag given by de Vaucouleurs and de Vaucouleurs (1972) within a 114″ aperture. With a distance of 60 Mpc and a galactic absorption of 0.28 mag, the total absolute B magnitude is −21.6 mag, a value which places NGC 128 among the brightest galaxies known.

For further applications, the light density on the equatorial plane has been computed from a double exponential smoothing of the luminosity profile along the major axis (Fig. 2, *dashed line*) using formula (2) of Paper I. The ratio between the apparent and the true axial ratios is placed equal to 1, since we assume, in agreement with Sandage (1961) and Hodge and Merchant (1966), that NGC 128 is most likely an edge-on galaxy. Values of the light density $\psi(r)$, evaluated at several distances from the center, are given in Table 2.

IV. THE ROTATION CURVE OF NGC 128

In order to derive the rotation curve of NGC 128, three spectra along the estimated major axis (P.A. 0°) were taken with the 200 inch Cassegrain image-tube spectrograph, the same instrument used to investigate NGC 4697 (Paper I). Two additional spectra were obtained at the same position angle but displaced by 8″ on each side of the nucleus to cover the bumps of the box-shaped structure. Finally, one spectrum of the nuclear region has been recently taken with the Ritchey-Chrétien image-tube spectrograph attached at the 4 m Mayall telescope which, for both linear scale (27″ mm^{-1}) and dispersion (54 Å mm^{-1}), allows the investigation of the inner rotation curve. All this material has been listed in Table 3.

On the Palomar spectra, covering the range from 3300 to 5000 Å, the H and K absorption lines of Ca II are dominant, while the G-band appears shallow. There is also a slight indication of the presence of the [O II] doublet emission at 3727–3729 Å. The KPNO spectrum, ranging from 5500 to 7000 Å, exhibits only the blend, slightly resolved, of the absorption D lines of Na I. There is no evidence of any emission, while Burbidge and Burbidge (1965) observe the [N II] lines. We might account for this disagreement by assuming that the [N II] emission is confined within the innermost nucleus (< 5″), where our spectrum is rather overexposed. However, in a spectrum (B1379) taken with the McDonald B spectrograph by G. de Vaucouleurs, who kindly made it available to us, again no trace of emission features is found.

The H and K lines appearing on the Palomar spectra were measured on a Grant machine and reduced as described in Paper I. Special care was used in weighting the velocities from the two lines in the outer regions where emissions from the sky, which affected the preliminary reductions (Bertola 1972), are present. Because of the redshift, there is no contamination at all from the H and K sky lines. The final mean radial velocities as function of the distance from the center have been listed in Table 4 and plotted in Figure 3 (*lower panel*). Reliable measurements were possible up to a distance of about 40″ from the center (corresponding to the considerable extent of 11.6 kpc), where the surface brightness of NGC 128 is μ_B = 22.7 mag $arcsec^{-2}$.

The two spectra across the bumps (Q759 and 760 in Table 4) were treated in the same way. Mean radial velocities as function of the distance from the minor axis are given in Table 4 and plotted in the upper panel of Figure 3. Although these spectra were recorded and measured over the full length of the slit, only the values from points close to the minor axis were judged to be reliable. For these values, as can be easily seen in Figure 3, the trend is the same as for the spectra crossing the nucleus.

The D doublet on the KPNO spectrum (Fig. 4) was

TABLE 3

NGC 128: Spectroscopic Material

No.	Date	Exposure (minutes)	Remarks
Q613..........	1968 Sept. 22	10	Nucleus centered
Q743..........	1968 Oct. 22	30	Nucleus centered
Q744..........	1968 Oct. 22	30	Nucleus centered
Q759..........	1968 Oct. 23	30	Nucleus offset 8″ east
Q760..........	1968 Oct. 23	30	Nucleus offset 8″ west
KPNO 636.....	1975 Feb. 8	80	Nucleus centered
Q614..........	1968 Sept. 22	10	NGC 127 centered
Q615..........	1968 Sept. 22	10	NGC 130 centered

Note.—All spectra have been taken at P.A. 0°.

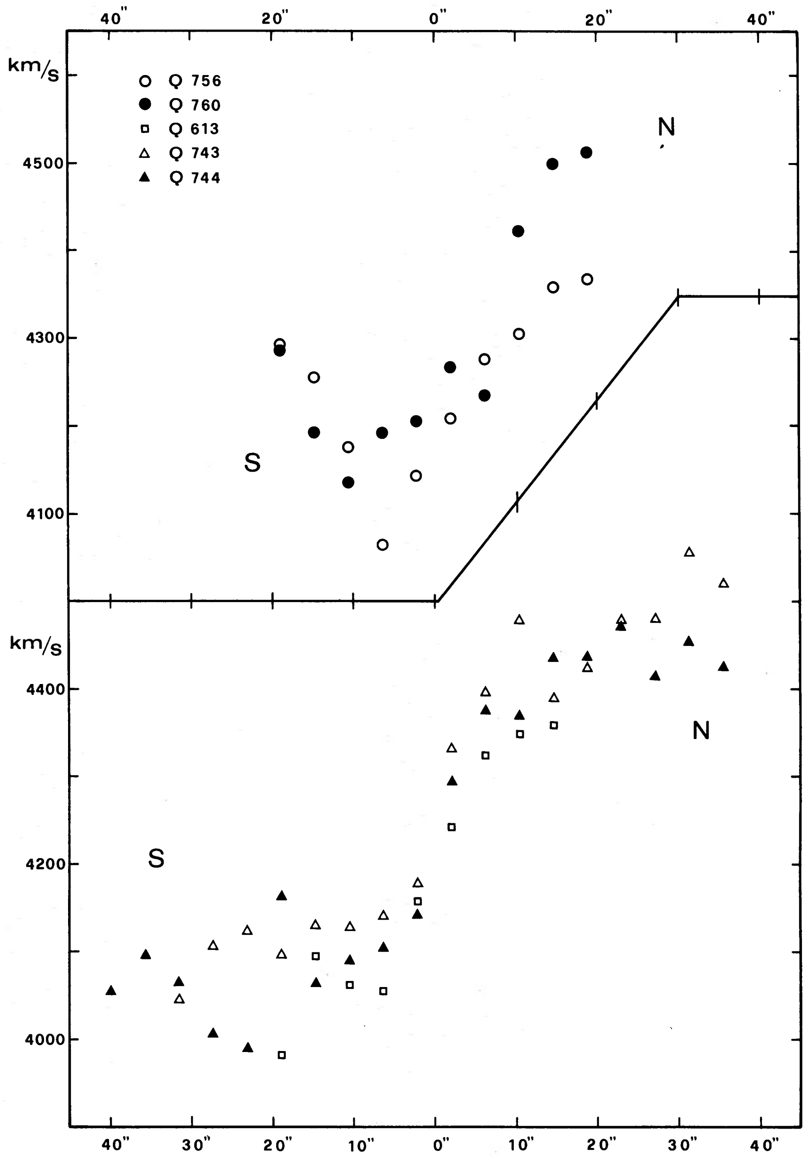

Fig. 3.—*Lower panel*, observed heliocentric radial velocities as function of the distance from the center along the major axis of NGC 128 from three Palomar spectra. *Upper panel*, the same for the two spectra taken with the slit offset 8″ each side from the center. Distances are from minor axis.

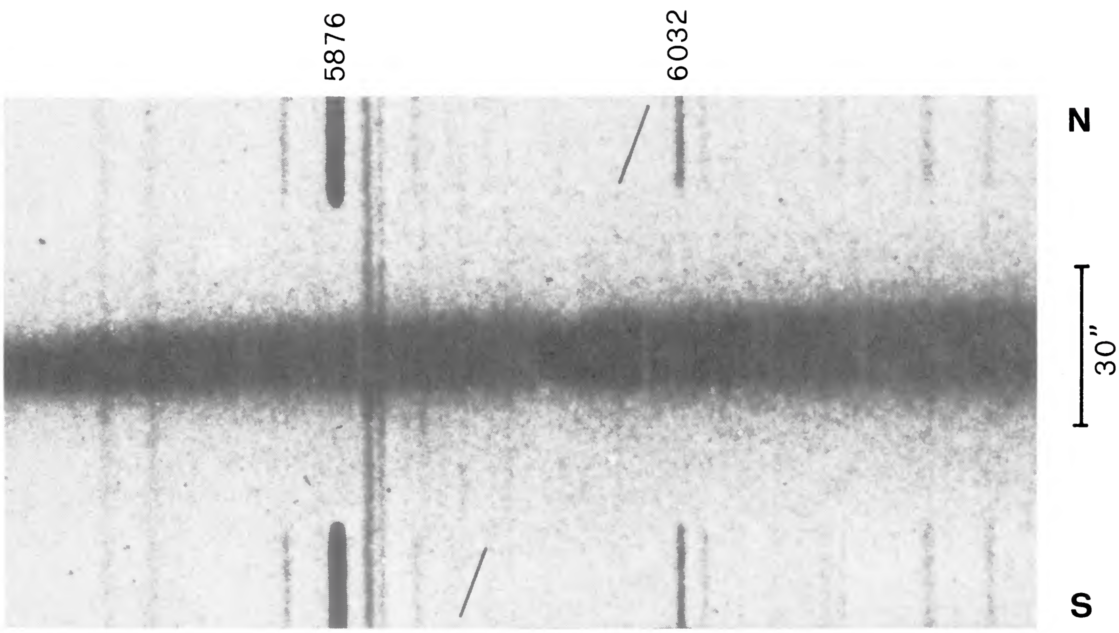

FIG. 4.—Reproduction of the spectrum No. 636 of NGC 128 taken with the image-tube spectrograph attached at the R-C focus of the 4 m KPNO telescope. Marks show the tilt of Na I D lines in the nucleus.

TABLE 4

NGC 128: Heliocentric Radial Velocities along P.A. 0°

Distance from Center (arcsec)	Velocity (km s⁻¹)				
	Q613	Q743	Q744	Q759	Q760
S −39.9.........	...	...	4055	...	...
−35.7.........	...	...	4097	...	...
−31.5.........	...	4045	4065	...	...
−27.3.........	...	4106	4007	...	...
−23.1.........	...	4124	3990	...	...
−18.9.........	3982	4096	4163	4293	4287
−14.7.........	4095	4130	4064	4256	4193
−10.5.........	4062	4128	4090	4176	4137
− 6.3.........	4055	4141	4105	4065	4193
− 2.1.........	4158	4178	4142	4144	4206
+ 2.1.........	4242	4332	4295	4209	4268
+ 6.3.........	4324	4396	4375	4277	4236
+10.5.........	4349	4479	4370	4306	4423
+14.7.........	4359	4389	4437	4359	4500
+18.9.........	...	4424	4438	4368	4513
+23.1.........	...	4477	4474	...	...
+27.3.........	...	4481	4415	...	...
+31.5.........	...	4556	4455	...	...
N +35.7.........	...	4520	4426	...	...

Note.—See Table 3 for references.

used to obtain the velocity gradient in the nuclear region by measuring the inclination of the lines with respect to the direction of dispersion. We obtain a slope of 40 km s^{-1} $arcsec^{-1}$ over a region of 4″ each side from the center. Such a value is, of course, higher than that derived from the Palomar spectra, where the effect of the lower scale and the smoothing due to the integration of the scanning slit of the measuring machine are present. The same situation was found in Paper I when we compared our value for the central slope of the rotation curve of NGC 4697 to that given by King and Minkowski (1966).

In Figure 5 we have plotted the mean points from the three Palomar spectra taken along the major axis. The two sides were folded together assuming a systemic heliocentric velocity of 4250 km s^{-1}. On the same figure we have also represented the central slope up to 4″ from the nucleus measured on the KPNO spectrum. The solid curve drawn through these data is a smoothed continuous representation of the observed rotation curve of NGC 128. The dashed part (from 4″ to 10″) stays to indicate uncertainty in the region where the information obtained is not fully reliable. The rotation curve shows that the central steep increase of velocity is followed by a shallow minimum weakly suggested by the measurements on both sides of the galaxy. Then the rotation curve rises to a value of 200 km s^{-1}, which is rather constant to the limit of the observations.

V. ANALYSIS AND DISCUSSION

Morphological and photometric considerations show that S0 galaxies, unlike ellipticals, consist of two subsystems, a flat disk and a spheroidal component, with different dynamical properties. The disk is supposed to rotate with almost circular velocity, while the

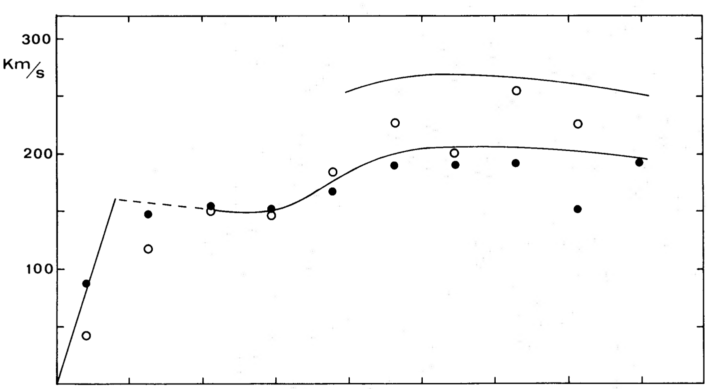

Fig. 5.—Circles give the mean values of the radial velocities from three Palomar spectra as functions of the distance from the center along the major axis of NGC 128 (*open*, north side; *filled*, south side). The central steep gradient, measured on the high-resolution KPNO spectrum up to 4″ from the nucleus, is tentatively connected by a dashed line to the smoothed representation of the outer rotation curve. The upper curve gives the outer branch of the circular velocity curve of NGC 128 (see text).

spheroidal component possesses, in addition to rotation, a significant amount of random motions. NGC 128, except for some peculiarities, has the characteristics of an S0 galaxy. Therefore it is intriguing to disentangle from the observations the amount of rotation belonging to each component. In other words, here formula (1) of Paper I, which was used there in deriving the spatial velocity by deprojection of the rotation curve, does not have a unique solution, since we are dealing with a two-subsystem model. However, we can rather safely perform the deprojection in the outer parts, where the disk becomes prominent over the spheroidal component. In fact, the analysis of the luminosity profile along the major axis (Fig. 2) shows that the exponential component characteristic of the disk merges at about 20″ from the nucleus. This is confirmed by direct inspection of the image of NGC 128 (Sandage 1961) where the disk protrudes from the box-shaped bulge at about 20″ from the nucleus. Therefore we compute the spatial velocity of NGC 128 only in the range from 20″ up to the last observed point at 40″. We assume, as in Paper I, that the galaxy is completely transparent and seen edge-on, and that the weighting function is the spatial luminosity distribution $\psi(r)$ derived in § III and given in Table 2. We solved numerically the integral equation (1) given in Paper I in the interval $20'' \leq r \leq 40''$, using a smoothed representation of the corresponding branch of the rotation curve and a constant value extrapolation. On the basis of the results achieved in Paper I, we do not have to worry about how to extrapolate the observed rotation curve while performing the deprojection. The computed part of the rotation curve is shown in Figure 5.

In a first approximation we can assume that, in the disk, the random motions are negligible with respect to the rotation. Therefore the branch of the spatial velocity curve, previously derived in the range $20'' \leq r \leq 40''$, coincides with the circular velocity. The knowledge of this branch of the rotation curve allows us to compute the mass of NGC 128 up to the last observed point. Simple calculations show that the mass of the galaxy does not vary more than 10%, whatever reasonable way is assumed to connect the origin to the branch of the rotation curve starting at 20″. The mass within 40″ from the nucleus, derived using the spheroidal model (Burbidge, Burbidge, and Prendergast 1959) of axial ratio 0.3, as indicated by our photometry, is around the value of $1.4\ 10^{11}\ M_\odot$. Using the luminosity within 40″ from the nucleus, we obtain a mean mass-to-light ratio $M/L_B = 7$.

These values are of the same order of those usually found for spirals. This is not surprising, since the branch of the circular velocity curve of NGC 128 is very similar, in both shape and amount of velocity, to the corresponding parts of the rotation curves of many spiral galaxies (see, e.g., the rotation curves of the Galaxy, M31, M81, and M101 as given by Roberts and Rots 1973). The same similarities can also be found in the rotation curve of the other recently studied S0 galaxy NGC 3115 (Williams 1975), even though it extends less than that of NGC 128. Therefore we are induced to argue that the dynamical behavior of S0 galaxies, at least as far as the disk is concerned, is close to that of spirals. This conclusion is supported by the results obtained by Sandage, Freeman, and Stokes (1970). They showed that spiral galaxies and S0's possess the same distribution of true axial ratios, which can be interpreted as a consequence of similar angular momenta. On the other hand, our result supports the recent classification scheme proposed by van den Bergh (1976) where the S0 galaxies, no longer considered as a transition phase between E and S, are placed in a sequence parallel to that of spirals.

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