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EXTENDED ROTATION CURVES OF HIGH-LUMINOSITY SPIRAL GALAXIES. I. THE ANGLE BETWEEN THE ROTATION AXIS OF THE NUCLEUS AND THE OUTER DISK OF NGC 3672

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ABSTRACT

A large velocity gradient is observed in the excited nuclear gas of NGC 3672 when the slit is aligned along the minor axis, and a nuclear velocity gradient smaller than that implied by the rotation curve of the outer disk is observed with the slit along the major axis. The most direct interpretation of this observation is that the rotation axis of the nuclear gas disk makes a large angle with the rotation axis of the outer galaxy as a whole. An alternative explanation is that the nuclear gas is not rotating but is contracting ($\sim$50 km s^{-1}) in the plane of the outer disk. Both models imply that we are observing a transient phenomenon. The nucleus is small, $r < 350$ pc, and of low mass, $\sim 2 \times 10^8 \, M_\odot$, compared with a galaxy mass of $1.4 \pm 0.2 \times 10^{11} \, M_\odot$.

Subject headings: galaxies: internal motions — galaxies: individual — galaxies: general

I. INTRODUCTION

A major unsolved problem of galactic dynamics concerns the relation of the rotation axis of the nucleus of a galaxy to the rotation axis for the entire galaxy. Present indirect evidence indicates that these two spin axes can be significantly different. For radio galaxies, large angles between the radio axes and the rotation axes of the parent elliptical galaxies are quite common. Because there are reasons for believing that the radio axes coincide with the nuclear rotation axes (Oort 1977), this implies that nuclei of elliptical galaxies can rotate in planes different from the equatorial planes of the galaxies as a whole.

On a smaller scale, it is likely that the nucleus of M31 is oriented so that its rotation axis is not parallel to the rotation axis of the outer galaxy. Stratoscope II observations (Light, Danielson, and Schwarzschild 1974) indicate that for $r \sim 0''.3$ (1 pc), the nucleus of M31 is elongated in position angle PA = 70°, but with increasing r the position angle of the major axis decreases, until at $r \sim 10$ kpc the major axis coincides with that of the outer disk, PA = 38° (Johnson 1961; Peterson, Ford, and Rubin 1977 and references therein). Even though these observations span the blue through the red spectral regions, it is not yet certain if the observations indicate a dynamical effect, or if the nuclear contours are distorted by the dust which extends very close to the nucleus.

We present dynamical evidence that the motion of the gas in the nucleus of the spiral galaxy NGC 3672 is more complex than simple rotation in the plane of its outer galactic disk. NGC 3672 (Sc II [van den Bergh 1976]; $\alpha_{1950} = 11^{\mathrm{h}}22^{\mathrm{m}}.5$, $\delta = -9°31'$; $l = 270°$, $b = +48°$) is an attractive multi-armed spiral, undistinguished optically except for the small angular extent of its nucleus (Sandage 1961). A deep 4 m CTIO blue plate is reproduced in Figure 1 (Plate L1). From radio observations with the NRAO 91.4 m transit telescope,[1] NGC 3672 has a broad ($\Delta V > 400$ km s^{-1}) 21 cm velocity profile (Fig. 2) arising from a combination of its high inclination and its high intrinsic luminosity. (Tully and Fisher [1977] have emphasized the relation between high luminosity and broad ΔV). Of 150 bright ($m < 14$) spiral galaxies for which we have obtained 21 cm observations (Thonnard, Rubin, Ford, and Roberts, unpublished), NGC 3672 is one of about 40 galaxies which has a velocity profile of width greater than 400 km s^{-1}. For a sample of these broad-profile galaxies, we are obtaining optical spectra to investigate the detailed optical rotation curves at large distances from the nucleus.

II. THE OBSERVED VELOCITIES AND THE NUCLEAR ROTATION AXIS

Emission-line spectra of NGC 3672 were obtained with the CTIO 4 m image tube spectrograph in 1977 March; the high spatial and high velocity resolution of the instrument was exploited by using baked, preflashed IIIa-J plates, with the transfer optics stopped down to f/2.0. The dispersion is 50 Å mm^{-1}; the scale perpendicular to the dispersion is $23''.54$ mm^{-1} (Schweizer 1977). A slit width of 200 μm ($1''.3$) was used. The seeing was probably $1''.5$ or better; a more accurate measure cannot be given by the observer who views a TV screen. The width of the nuclear continuum, which subtends $\sim 1''.5$ on the plates, arises from a combination of the true nuclear extent, the seeing, and tracking and guiding effects.

With the spectrograph slit aligned along the major axis of the outer galaxy, PA = 8° (Fig. 1) the rotation pattern of the outer galactic disk is observed. Along the minor axis, PA = 98° (Fig. 1) no significant

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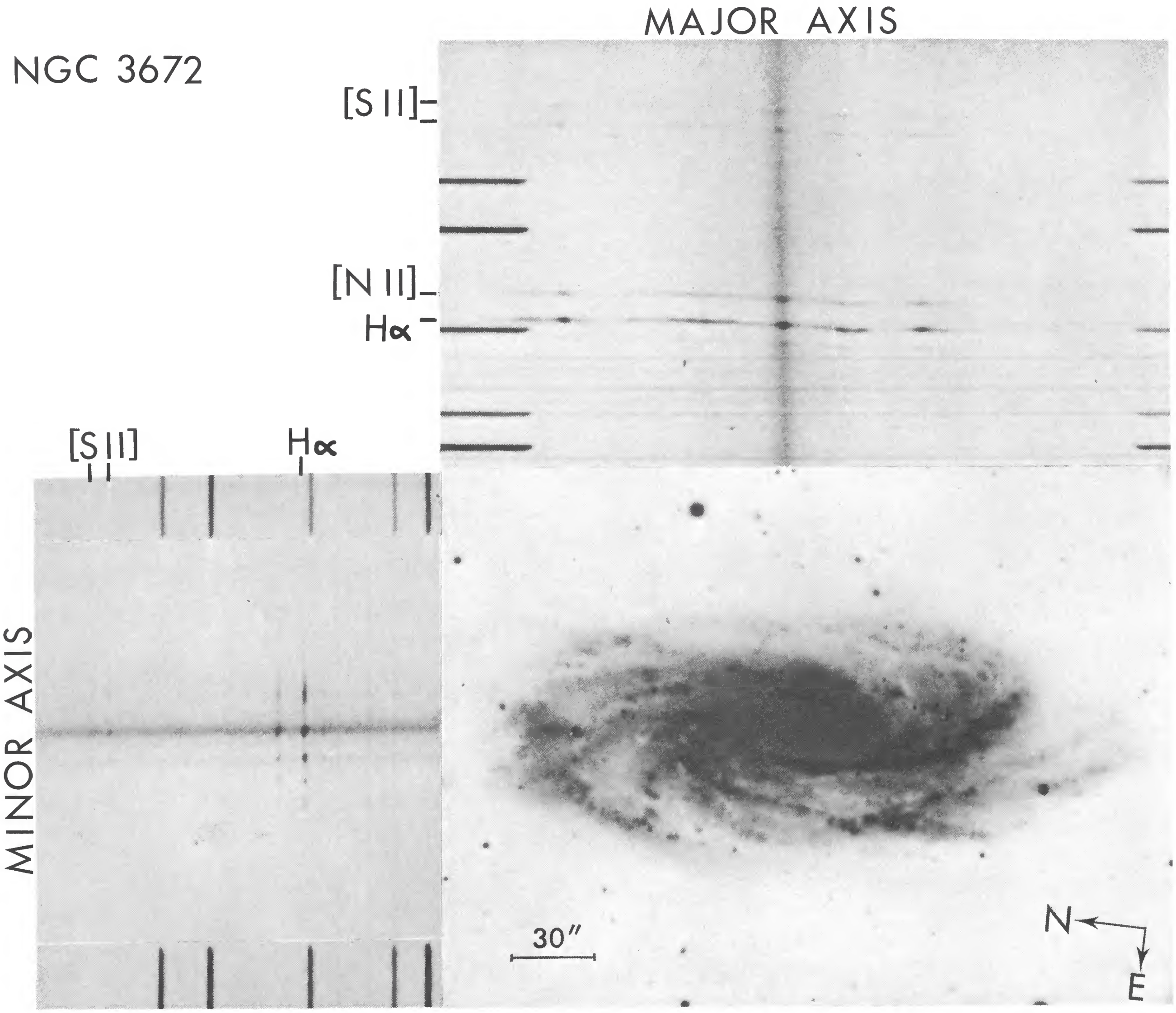

FIG. 1.—NGC 3672 from a 4 m CTIO plate; N_2 baked IIIa-J plate +GG385 filter; exposure 90^m. Print is oriented so that major axis (PA = 8°) is horizontal.

Major axis spectrum; original dispersion 50 Å mm^{-1} on N_2 baked and preflashed IIIa-J; exposure 120^m. Spectrum is printed to same scale as galaxy so individual features may be identified.

Minor axis spectrum, exposure 70^m. Note inclination of nuclear emission on Hα, [N II], and [S II].

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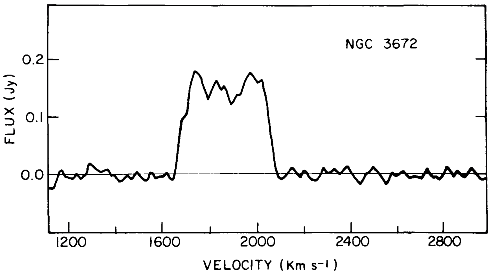

FIG. 2.—Neutral hydrogen flux density observed in NGC 3672 with the NRAO 300 foot (91 m) radio telescope. Heliocentric velocity is in the opical convention; $V = c\Delta\lambda/\lambda_0$. Flux density has not been corrected for galaxy size; if the neutral hydrogen size were the same as the optical image, the flux density should be increased by 11%.

velocity difference is observed in the NW and SE outer emission knots; $\langle V\rangle_{\rm SE} = 1857 \pm 3$ km s^{-1}, and $\langle V\rangle_{\rm NW} = 1859 \pm 4$ km s^{-1}. However, a large velocity gradient across the nuclear emission knot is observed along the minor axis. Equally interesting, a small nuclear velocity gradient is seen along the major axis, smaller than would be expected from the linear portion of the outer rotation curve. Measured velocities are listed in Table 1 and shown in Figure 3. These observations imply either that the nuclear rotation axis is not coincident with that of the galaxy as a whole, or that the nuclear gas is not rotating but is contracting in the plane of the galaxy. We first discuss the model with nonaligned axes.

For the nuclear gas, emission-line velocities are measured over $4''.7$ (major axis) and $3''.4$ (minor axis). The observed velocity gradients are (least squares fits; Hα given double weight in PA = 8°):

$$\text{PA } 8^\circ\text{: } -2.7 \pm 1 \text{ km s}^{-1}\text{ arcsec}^{-1} \quad \text{(outer disk major axis)}\,,$$

$$\text{PA } 98^\circ\text{: } -29.5 \pm 1 \text{ km s}^{-1}\text{ arcsec}^{-1} \quad \text{(outer disk minor axis)}\,.$$

In contrast, the velocity gradient of the linear portion of the major axis rotation curve is -6.0 km s^{-1} arcsec^{-1}. These values are uncorrected for the effects of seeing. Depending on details of the models, a $1''.5$ seeing disk will cause the true velocity gradient in PA 98° to be measured 7%–35% too small. The minor axis gradient is larger than we measure.

If the nuclear gradients arise from a nuclear disk rotating with constant angular velocity, then the position angle of the dynamical major axis ϕ of the nuclear disk is

$$\tan\phi \approx \frac{-29.5\cos 8^\circ - (-2.7)\cos 98^\circ}{-2.7\sin 98^\circ - (29.5)\sin 8^\circ}\,,$$

$$\phi \approx 93^\circ\,,$$

compared to $\phi = 8^\circ$ for the outer disk. Thus the angle between the major axis of the nuclear gas disk and the outer stellar disk is close to 90°. Because we have no velocities for the stellar population in the nucleus, it is

TABLE 1

VELOCITIES (Heliocentric) IN NGC 3672

MINOR AXIS PA=98°		MAJOR AXIS PA=8°					
y (arcsec)	v (km s^{-1})	y (arcsec)	v (km s^{-1})	y (arcsec)	v (km s^{-1})	y (arcsec)	v (km s^{-1})
Hα:		Hα:					
−32.6 SE	1850	−111.0 NE	2044	+16.1	1757	−49.5	2021
−27.1	1861	−106.2	2018	+20.9	1696	−44.8	2033
−23.4	1866	−101.5	2017	+25.6	1668	−40.0	2022
−19.0	1852	−96.8	2011	+30.3	1682	−35.4	2017
−18.8	1850	−92.1	2030	+32.7	1675	−30.8	2003
−10.0	1869	−87.4	2035	+39.7	1705	−26.0	1991
−1.7	1901	−82.7	2030	+44.4	1695	−21.2	1966
0	1861	−80.8	2023	+49.2	1996	−16.5	1962
+1.7	1803	−78.0	2026	+51.3	1692	−11.8	1931
+4.8	1854	−73.3	2020	+53.8	1688	−7.1	1892
+8.8	1874	−68.6	2008	+58.5	1655	−2.4	1882
+12.0	1869	−59.1	2047	+63.3	1677	+0.1	1855
+13.9	1871	−54.4	2037	+67.8	1665	+2.3	1852
+16.5	1857	−49.8	2047	+72.7	1658	+6.9	1833
+17.7	1840	−45.0	2039	+77.4	1633	+11.6	1805
+21.4	1849	−40.3	2038	+82.1	1610	+16.4	1772
+24.1	1869	−35.6	2015	+96.2	1668	+21.1	1707
+38.8 NW	1894	−30.9	1999	+101.0 SW	1658	+25.8	1687
[N II]:		−26.1	1976	[N II]:		+30.5	1673
−10.4	1864	−21.4	1972	−96.6 NE	2040	+35.2	1689
−1.1	1889	−16.8	1944	−91.9	2045	+39.9	1708
+1.1	1817	−12.1	1909	−87.2	2041	+44.6	1679
+6.4	1864	−7.4	1884	−82.4	2033	+49.4	1686
+13.1	1868	−2.7	1861	−80.8	2021	+51.6	1686
+19.6	1848	+0.2	1858	−77.7	2020	+54.1	1694
[S II]:		+2.0	1857	−73.0	2012	+58.8	1692
−1.0	1889	+6.7	1840	−58.9	2019	+62.8 SW	1697
+1.3	1820	+11.5	1810	−54.2	2031		

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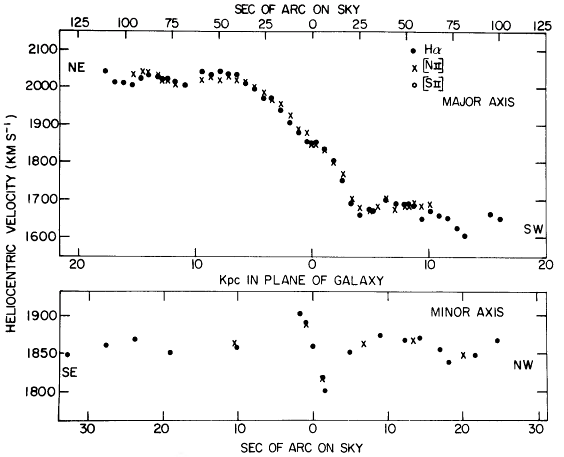

FIG. 3.—*Upper*, major axis heliocentric velocities on plane of sky, as a function of distance from the nucleus. *Lower*, minor axis velocities as a function of distance from the nucleus; note change in scale from upper plot. The steep velocity gradient in nuclear region along minor axis is prominent.

not known if the stars and the gas show a common rotation axis.

By analogy with M31, we would like to know if the nucleus of NGC 3627 is elongated in PA = 93°. Our plate material is not adequate to answer this question because the two spectra are of unequal exposure (120^m and 70^m) and the direct plate is too deep.

The mass of the nucleus of NGC 3627 is small. At a distance of 33 Mpc for NGC 3672 (see below), $1'' =$ 160 pc. The nucleus is about 350 pc in radius: the uncertainty arises from the unknown inclination. The observed velocity at the edge of the nucleus, 50 km s^{-1}, corresponds to a rotational velocity in the plane of the nuclear disk of about 80–100 km s^{-1} for inclinations in the range 70°–30°. These values imply a mass of order 2×10^8 $M_\odot$, $r < 350$ pc. This mass is an order of magnitude less than that within $r = 200$ pc in our Galaxy (Oort 1977); it is about 3 times less than in the nucleus ($r < 200$ pc) of M31 (Rubin and Ford 1970). A low-mass nucleus might enhance the likelihood of a large angle between the rotation axis of the nucleus and the outer disk. We return to a discussion of this in § IV below.

The alternative explanation of these observations is that the gas in the nuclear region, $r \leq 350$ pc, is contracting with $V \sim 50$ km s^{-1} in the plane of the disk, and not rotating. (With the spiral arms trailing, the east side is the near side, and the radial motion is a contraction.) This model will produce the low velocity gradient seen along the major axis, and the high gradient along the minor axis. From the velocities alone, we cannot distinguish between these two models.

III. THE MASS OF NGC 3672

The heliocentric velocity of NGC 3672 is well determined as $V_c = 1857$ km s^{-1} (1857 from nuclear velocities on the major axis plate, 1856 from nuclear measures on the minor axis plate; 1857 from the SE minor axis; 1859 from the NW minor axis), which corresponds to $V = 1655$ km s^{-1} corrected for the motion of the Sun with respect to the Local Group. We adopt a distance $D = 33$ Mpc. On the 4 m plate, the main body and arms extend to $r = 111'' = 17.8$ kpc. Emission lines are observed over this entire extent. A few fainter knots are observed out to $r = 23.7$ kpc (but not along the major axis). The inclination i of the galaxy is in the range 70°–75°. The observed velocities along the major axis, when multiplied by csc $i \sim 1.05$, become rotational velocities in the plane of NGC 3672.

The observed velocities are reasonably symmetric about $r = 0$; the major exceptions are the steeper rise on the SW side, and the larger variation at larger r. Uncertainties in any velocity should not exceed 10 km s^{-1}, so the dips in the rotation curve are real. A mean rotation curve has been adopted (Fig. 4) and rises to 195 km s^{-1} (206 km s^{-1} in the plane of the galaxy) at $r = 14.4$ kpc. The mass implied by this rotation curve is $M = 1.1 \times 10^{11}$ $M_\odot$, out to $r = 17.6$ kpc.

The observed peak-to-peak Hα velocities along the major axis give $\Delta V = 400$ km s^{-1}, which agrees well with the observed 21 cm value, $\Delta V = 435$ km s^{-1}. Note that the Hα peak-to-peak velocity is a 1".3 wide sample along the major axis of the galaxy whereas the 21 cm profile width is the integral of all the neutral hydrogen in the galaxy. The central velocity from the 21 cm profile is 10 km s^{-1} higher than the optical velocity. The integrated H I flux density, corrected by 11% for galaxy size, is 65 Jy km s^{-1}. Therefore the H I mass at the adopted distance is $M_{\text{H I}} = 1.9 \times 10^{11}$ $M_\odot$. With $m = 11.66$ (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) and $A = 0.13$ csc $|b|$, the distance-independent ratio, hydrogen mass to optical luminosity, is $M_{\text{H I}}/L_{\text{opt}} = 0.47$.

The total mass determined from $\Delta V = 416$ km s^{-1}, the 21 cm profile width measured at 20% of the peak intensity, is given by

$$M_T = 1.7 \times 10^{-2} D_{\text{pc}} d' (\Delta V/2)^2 / \sin i^2$$
$$= 1.5 \times 10^{11} M_\odot ,$$

where D is the galaxy distance in parsecs and d is the diameter in arcmin (Roberts 1969). This relation assumes that the rotation curve is a Brandt (1960) curve with $n = 3$ (equivalent to a Bottlinger curve), and that the peak velocity of the rotation curve comes at a distance $r_{\max}$ equal to one-third of the Holmberg radius. If we arbitrarily equate the Holmberg radius

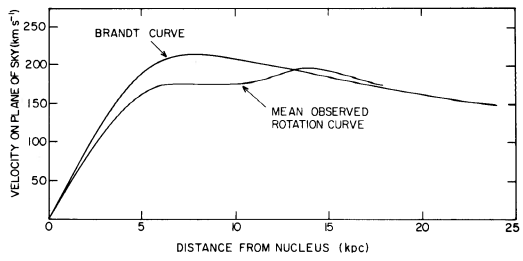

FIG. 4.—Adopted rotation curve for NGC 3672 compared with Brandt curve with $n = 3$, $r_{\max} = 8$ kpc, and $V_{\max} = \Delta V_{21\,\text{cm}}/2$. Velocities in the plane of the galaxy equal 1.05 times the velocities on the plane of the sky.

with the outermost observable knots, $r = 24$ kpc, then $r_{\max} = 8$ kpc. The Brandt curve with $n = 3$, $r_{\max} = 8$ kpc, and $V_{\max} = \frac{1}{2}\Delta V_{21\ \mathrm{cm}} = 218$ km s^{-1} (on the plane of the sky) is compared with the adopted rotation curve in Figure 4. It rises more steeply, and to a higher maximum than the observed curve, but is a good fit at large r. A Brandt curve with $V_{\max} = 200$ km s^{-1} may be a better fit to the total curve. The mass implied by this latter form is $1.4 \times 10^{11}\ M_{\odot}$.

The optical rotation curve gives $M_T = 1.1 \times 10^{11}\ M_{\odot}$, to $r = 17.6$ kpc. Extrapolating the observations to $r = 24$ kpc by (*a*) velocities decreasing as the Brandt curve and (*b*) velocities remaining constant at $V = 176$ km s^{-1} should give lower and upper limits to the total mass. Calculations give (*a*) $M = 1.2 \times 10^{11}\ M_{\odot}$, and (*b*) $1.4 \times 10^{11}\ M_{\odot}$. We adopt $M_T = (1.4 \pm 0.2) \times 10^{11}\ M_{\odot}$ as the total mass of NGC 3672 for the adopted distance, of which 10% is neutral hydrogen.

IV. CONCLUSIONS

There is a large velocity gradient across the excited nuclear gas of NGC 3672 when the slit is aligned along the minor axis, and a nuclear velocity gradient smaller than that implied by the rotation curve when the slit is aligned along the major axis. The most direct interpretation of this observation is that the rotation axis of the nuclear gas disk makes a large angle with the rotation axis of the outer galaxy as a whole. The nucleus is small, $r \sim 350$ pc, and of low mass, $\sim 2 \times 10^8\ M_{\odot}$, compared with a total mass of $(1.4 \pm 0.2) \times 10^{11}$ for the entire galaxy.

For a galaxy with a small, low-mass nucleus, the spin axis of the nucleus may represent merely the resultant angular momentum from the turbulent clouds which collapse to the center. Their initially randomly oriented angular momentum vectors might bear no relation to the outer disk of the galaxy. In our vicinity of the Galaxy, stellar axes of rotation have no preferred orientation with respect to the galactic plane. Because a nonaligned rotating nuclear disk cannot be stable on a time scale of rotation periods, we must be observing a transient phenomenon. The galaxy morphology shows little evidence of newly accreted gas, although the emission-line strengths (H$\alpha >$ [N II] as in unevolved gas), the massive dust regions on the W (far) side, and the group membership (de Vaucouleurs 1975) would allow room for such speculation.

In order to account for the observations of the nucleus of M31, a novel model of galactic nuclei has been advanced by Tremaine, Ostriker, and Spitzer (1975). Tidal friction near the nucleus ultimately captures globular clusters, forming a small compact nucleus of mass $\sim 10^7$–$10^8\ M_{\odot}$. On this model, one would expect no relation between the rotation axes of the nucleus and the outer galaxy. Alternatively, models involving triaxial ellipsoids might be pertinent. Detailed observations of very nearby galaxies, as well as high-resolution observations of galaxies at the distance of NGC 3672, should help to settle the question of the relation of spin axes of nuclei and their galaxies.

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