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NGC 4650A: THE ROTATION OF THE DIFFUSE STELLAR COMPONENT

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ABSTRACT

NGC 4650A consists of two components, a diffuse central component (which looks much like an S0 galaxy), and a warped outer ring of H II regions. The projections of these two components onto the sky lie nearly perpendicular to each other. We have measured the rotation of the diffuse central component, and find that the ratio of rotation velocity at the last measured point to the central velocity dispersion, σ_0, is greater than unity. This is consistent with a wide range of models, spanning a continuum with rapidly tumbling prolate systems at one extreme and nontumbling oblate ones at the other. For the nearly prolate configurations and for the oblate ones the ring of H II regions is unstable to differential precession and will settle to a position angle closer to the projected major axis of the central component. However, there may be a relatively oblate (but still triaxial) configuration for which the ring lies in a stable closed orbit.
Subject headings: galaxies: individual — galaxies: internal motion — galaxies: structure

I. INTRODUCTION

Recently several authors have drawn attention to the prominent dust lanes present in a number of elliptical galaxies (Bertola and Galletta 1978; Kotanyi and Ekers 1979; Hawarden *et al.* 1981). At the same time, it has been realized that the well-known "spindle galaxy" NGC 2685 (Burbidge and Burbidge 1959; Sandage 1961; Schechter and Gunn 1978) is not a unique object; several similar systems composed of an elongated diffuse stellar component surrounded by a thin ring (or rings) of stars, dust, gas, and H II regions have been recognized (Zwicky 1967; Sérsic 1967; Strom 1981, private communication; Whitmore, Schweizer, and Rubin 1982; Arp and Madore 1983; Lauberts 1982). In both the ellipticals with dust lanes and the spindle-like galaxies the nonstellar material (dust and/or ionized gas) is located in a plane perpendicular or nearly perpendicular to the major axis of the diffuse component. Particular importance has been attached to establishing the true three-dimensional figures (oblate, prolate, or intermediate and therefore triaxial) of the diffuse stellar components in these systems since their formation, stability, and evolution depend critically on this question (van Albada, Kotanyi, and Schwarzschild 1982; Tohline and Durisen 1982; Heisler, Merritt, and Schwarzschild 1982).

There are, however, several differences between the ellipticals with dust lanes on the one hand and the spindle-like galaxies on the other. The most important difference lies in the ellipticity of the diffuse component, which is always large in the spindle galaxies. Another difference is that in the ellipticals with dust lanes the lanes are observed interior to the optical image of the galaxy, NGC 5128 being a most notable exception. By contrast, in the spindle-like galaxies the ring is well outside the outline of the amorphous component.

The differences in the appearance of these systems may in fact correspond to different dynamical situations. In the case of the ellipticals with dust lanes, the diffuse stellar component could be a triaxial stellar system, either stationary (Steiman-Cameron and Durisen 1982) or rotating about one of its principal axes (e.g., van Albada, Kotanyi, and Schwarzschild 1982). In the case of spindle-like galaxies the diffuse stellar component could be an S0 galaxy seen edge-on, with the ring being in a nearly polar orbit (Whitmore, Schweizer, and Rubin 1982; Steiman-Cameron and Durisen 1982).

If this interpretation is correct, the more face-on members of this class would be harder to recognize. An alternative explanation of the spindle-like galaxies is offered by Tohline and Durisen (1982), who argue that NGC 2685 is probably a tumbling prolate system.

In this paper we discuss the case of NGC 4650A, a relatively nearby spindle-like galaxy. With certain assumptions we calculate the lifetime of the ring in the case where the diffuse stellar component is an S0 galaxy seen edge-on. We then consider the alternative possibility where the diffuse stellar component is a tumbling prolate system, and show that the velocities observed in the ring and in the diffuse component render this configuration unlikely.

A photograph of NGC 4650A is shown in Figure 1. Sérsic (1967) first drew attention to the peculiar morphology of this galaxy. The velocity field of the gas in the ring has been measured by Laustsen and West (1980), who show that the ring rotates with NW receding.

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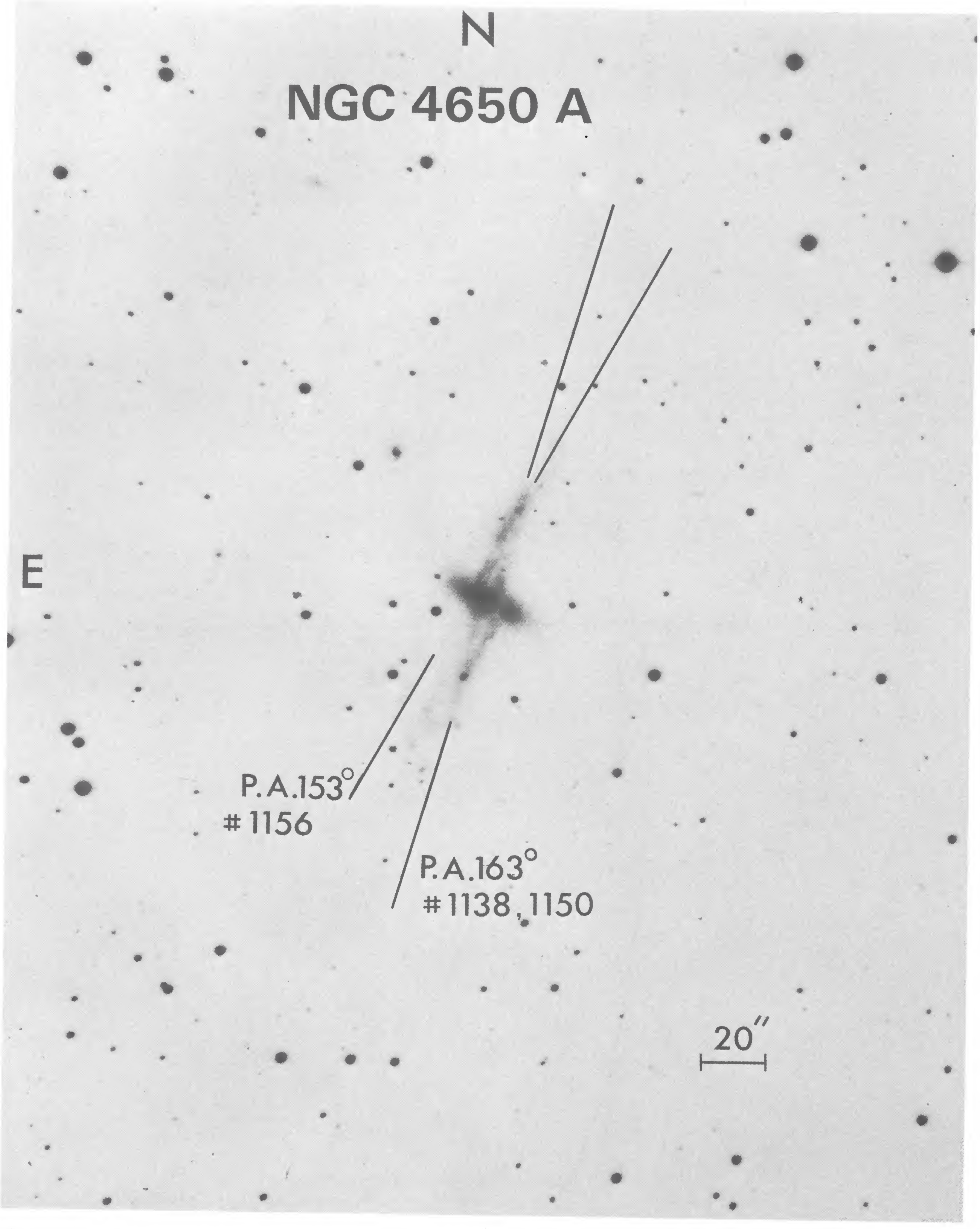

FIG. 1.—Reproduction of a photograph taken by S. Laustsen at the prime focus of the ESO 3.6 m telescope (Laustsen and West 1980). Exposure time 20 minutes. Emulsion and filter: IIIa-J+GG385.

TABLE 1

IPCS OBSERVATIONS

Object	Wavelength Range (Å)	Exposure (s)	Comments	P.A.	Slit
NGC 4650A	3432–4351	4400	...	70°	2″
NGC 4650A	3928–4835	7015	some cirrus	70°	2″
HD 151849	3928–4835	620	...	...	2″
HD 2713	3596–4814	600	Palomar	...	0″.5

Our discussion is based in part on new observations, the particulars of which are described in § II and the results of which are reported in § III.

II. OBSERVATIONS

We observed NGC 4650A on 1980 March 20 UT with the University College IPCS (Boksenberg 1978) at the Cassegrain focus of the ESO 3.6 m telescope. Details of these observations are given in Table 1. The position angle of the slit was chosen to pass through a nearby bright star, and therefore missed the major axis of the diffuse component (at P.A. 60°) by roughly 10°. Two wavelength regions were chosen, one to yield maximum velocity accuracy for a late type stellar population and one centered on the [O II] doublet at 3727 Å. A K0 giant and an F2 giant were also observed at the redder wavelength setting. The data were recorded in an array of 84 rows of 1500 spectral elements, with a resolution of roughly 2 Å FWHM along the spectra. Comparison spectra were taken before and after each exposure to monitor possible flexure and electronic shifts.

The data were reduced at KPNO, using the "RV" program on the Interactive Picture Processing System (IPPS). Dispersion solutions and curvature maps were obtained for the comparison spectra, which were then used to remove the curvature from the data frames and render them logarithmic in wavelength. S-distortion, always less than one pixel, was removed by shifting columns so that the galaxy or stellar spectrum was centered on one row. Sky data were obtained from the ends of the spectrum, and subtracted from the galaxy data. Rows of galaxy spectrum were then added together to give sufficient signal-to-noise to measure velocities.

Figure 2 shows the data for NGC 4650A from the bluer setting, summed over the central seven spatial increments, corresponding to 14″.8. The spectral type is obviously much earlier than the late G to early K typical of most elliptical galaxies, more like an early F star. To take full advantage of the Balmer lines evident in Figure 2, we obtained IPCS spectra of an F2 subgiant and an F2 supergiant with the Gunn-Oke Double Spectrograph at the Cassegrain focus of the Palomar 5 m telescope. These were observed at the same resolution, though with more wavelength coverage, and were reduced in the same fashion as the ESO data.

Velocities and velocity dispersions were measured using the Fourier quotient method described by Sargent *et al.* (1977). Since the fast Fourier transform algorithms require 2^N points, we used the bluest 600 Å of the red spectra and 600 Å of the blue spectra chosen to include most of the Balmer absorption observed in the galaxy's spectrum.

In addition to the IPCS data, long-slit spectra were obtained at a dispersion of 50 Å mm^{-1} along the ring and across the nucleus with the CTIO 4 m Cassegrain spectrograph. The positions of the slit are shown in Figure 1. The velocities of the ionized gas obtained from these spectra are given in the Appendix.

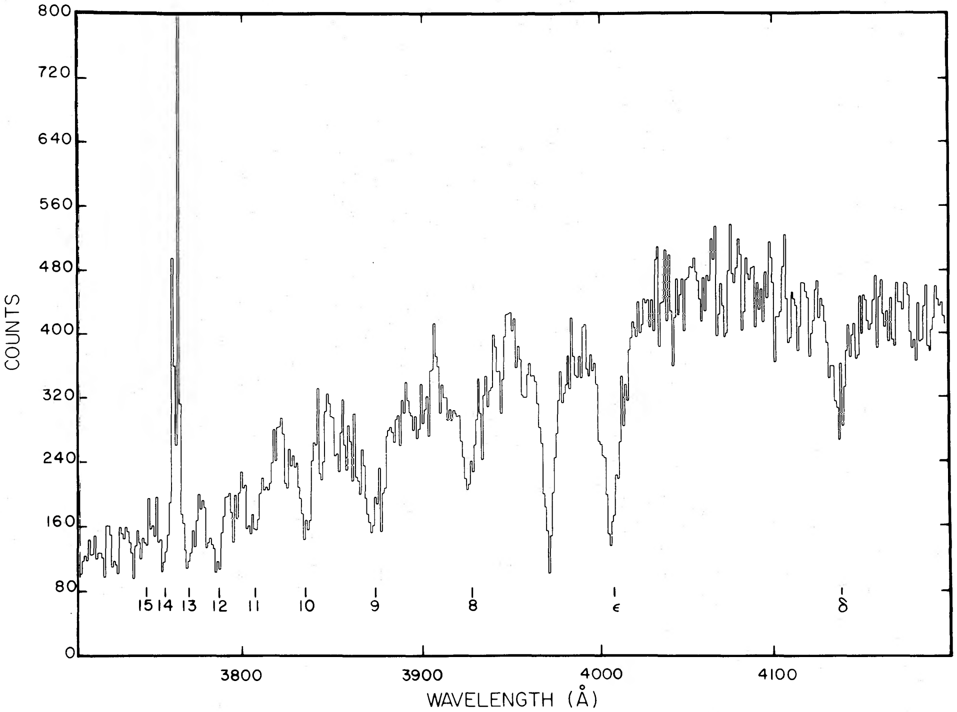

FIG. 2.—Counts summed over the central seven spatial increments versus wavelength from the bluer setting. Note that the spectral type is earlier than the late G or early K typical of most ellipticals.

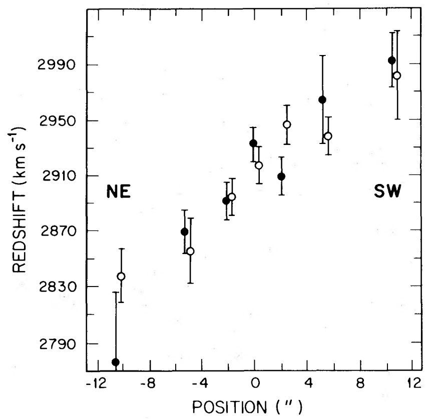

FIG. 3.—Rotation curve of the diffuse component of NGC 4650A. Open circles indicate velocities obtained at the redder setting; filled circles indicate the bluer setting.

III. RESULTS

Figure 3 shows velocity profiles for NGC 4650A obtained using HD 151849 (F2 III) as the comparison star for the red spectra and HD 2713 (F2 IV) as the comparison star for the blue spectra. The central amorphous component clearly exhibits rotation about its short axis. The central velocity dispersion, σ_0, determined from spectra summed over the central 14″.8, is 74 ± 10 km s^{-1}. If one takes the semiamplitude of the rotation curve to be ±80 km s^{-1} at the last point observed (10″.1 from the nucleus), the ratio of the observed rotation velocity to the central velocity dispersion is close to unity. The average heliocentric velocities obtained from the two sets of observations agree to within 10 km s^{-1}. Our IPCS measurements of the [O II] doublet give emission line redshifts of 2900 and 2913 km s^{-1}, respectively, for the 3726.1 Å and 3728.8 Å components, in excellent agreement with our absorption-line redshift.

IV. INTERPRETATION

a) *The Oblate Hypothesis*

The value of v_m/σ_0 observed for NGC 4650A is larger than any observed for a bona fide elliptical galaxy (Davies *et al.* 1983). Assuming that the light from the diffuse component comes from the superposition of a bulge plus an exponential disk, we determine a scale length for the disk (determined from our spectra) of roughly four pixels or 8″.5. Our outermost point on the rotation curve comes from little more than one scale length out in the disk. Were the rotation curve constant, we would expect to observe only 75% of the circular velocity, implying a ratio of $v_c/\sigma = 1.44$, consistent with the expected velocity for a bulge dominated system (Whitmore and Kirshner 1981). The hypothesis that the diffuse component is in fact an S0 would be tested by carrying the rotation curve measurements out another scale length, since one expects the rotation curve to flatten out between one and two scale lengths.

Our deprojected disk velocity of 107 km s^{-1} is very much smaller than the deprojected ring velocity of 180 km s^{-1} deduced by Laustsen and West (1980). If we use our value of 107 km s^{-1} to normalize the rotation curve expected for a Freeman (1970) disk, we find that we expect circular velocities of only 80 km s^{-1} at the position of the ring. While the deprojected ring velocity is quite sensitive to the assumed geometry of the ring, a "halo" with roughly 3 times the mass of the central diffuse component seems to be indicated.

If the oblate hypothesis is correct, the ring must precess about the axis of the putative S0 under the influence of the quadrupole terms in the galaxy's potential, with a frequency

$$\Omega_p = \tfrac{3}{2}\phi_2 r^{-2}\Omega_c^{-1}\sin\theta\,, \tag{1}$$

where

$$\phi_r = \phi_0(r) + \phi_2(r)P_2(\cos\theta) + \cdots \tag{2}$$

and where Ω_c is the orbital angular frequency (Gunn 1979). Here θ is the angle at which the ring is inclined to the pole—roughly 15° in the case of NGC 4650A (Laustsen and West 1980).

Since the ring is not infinitesimally narrow, gas clouds at different radii will precess at different rates. Mixing between the inner and outer parts of the ring will cause the ring to settle into the plane of the S0 (Tohline, Simonson, and Caldwell 1982). If the time scale for this process is short compared with the Hubble time, the ring would have to have formed relatively recently.

The time scale for this process is given by

$$\tau_s = \frac{\pi}{2}\left(\frac{d\Omega}{dr}\Delta r\right)^{-1} \tag{3a}$$

$$= \frac{\pi}{2}\left(\frac{d\Omega}{dr}\frac{\Delta v}{\kappa}\right)^{-1} \tag{3b}$$

$$= \frac{\pi}{2}\left(\frac{d\Omega}{dr}\frac{\Delta v}{\beta\Omega_c}\right)^{-1}, \tag{3c}$$

where Δr is the typical excursion in radius due to random velocities in the plane of the ring, Δv. Here κ is the epicyclic frequency, which we take equal to some constant of order unity, β, times the orbital frequency. It should be noted that equations (3a)–(3c) are derived more or less on dimensional grounds (Tohline, Simonson, and Caldwell 1982) and that the time scales obtained from them could easily be in error by a factor of 2 or more.

We shall consider two extreme cases: one in which all the mass is assumed to lie in a Freeman (1970) disk with scale length R, coincident with the light distribution, and a second (following Gunn 1979) in which the precession of the ring is dominated by the mass in some dark oblate halo with ellipticity ϵ_h and an r^{-2} density profile. We then have

$$\frac{\Omega_p}{\Omega_c} = \frac{9}{2}\left(\frac{R}{r}\right)^2 \sin\theta \quad \text{(Freeman disk)} \tag{4a}$$

$$= \tfrac{1}{2}\epsilon_h \sin\theta \quad \text{(oblate halo)}\,, \tag{4b}$$

where we have taken the quadrupole term of the potential $\phi_2(r)$ to be $3GMR^2/r^3$ for the Freeman disk. Differentiating and substituting into equation (3c), we find

$$\frac{\tau_{\rm H}}{\tau_p} = \frac{2}{\pi}\frac{63}{4}\left(\frac{R}{r}\right)^2 \frac{\Delta v}{V}\frac{\sin\theta}{\alpha} \quad \text{(Freeman disk)} \tag{5a}$$

$$= \frac{2}{\pi}\frac{1}{2\sqrt{2}}\epsilon_h \frac{\Delta v}{V}\frac{\sin\theta}{\alpha} \quad \text{(oblate halo)}\,, \tag{5b}$$

1984ApJ...277..526S

where τ_H is the Hubble time, $1/H_0$; V is the galaxy's redshift; α is the radius of the ring in radians; and where we have used the fact that $\beta = \sqrt{2}$ for a logarithmic potential (Richstone and Potter 1982) and 1 for a Keplerian potential. Note that the ratio of the Hubble time to the settling time is independent of the galaxy's mass and of the velocity of the gas in the ring.

A quantitative estimate of the settling time is obtained by letting $\alpha = 42''$ (Laustsen and West 1980), $V = 2190$ km s^{-1}, $\theta = 15°$, and $(R/r) = 0.2$. We take $\Delta v = 10$ km s^{-1}, comparable to the H I velocity dispersions observed in face-on spirals (van der Kruit and Shostak 1982), and $\epsilon_h = 0.3$, the typical ellipticity observed in elliptical galaxies (Binney and de Vaucouleurs 1981). We find

$$\frac{\tau_H}{\tau_s} = \begin{cases} 1.75 & \text{(Freeman disk)} \\ 0.29 & \text{(oblate halo)}\,, \end{cases} \tag{6}$$

indicating settling times comparable to the Hubble time, and sufficiently long that we are not forced to posit the recent accumulation of a gas-rich system by the parent S0. The relatively early spectral type of the central diffuse component does, however, suggest substantial recent star formation.

The differential precession mechanism does offer a possible explanation of the gap interior to the ring: the settling times there are shorter, and material there might not have survived a Hubble time.

b) *The Prolate and Triaxial Hypotheses*

Laustsen and West (1980) were led by the orientation of the ring in NGC 4650A to the conclusion that the diffuse stellar component is prolate. This explanation is not completely satisfactory, however, since the ring is not exactly perpendicular to the central component, but it tilted some 15° away. It would therefore precess in a stationary prolate field. Van Albada, Kotanyi, and Schwarzschild have proposed a mechanism which, at first glance, might account for this tilt. They consider a prolate or triaxial figure which tumbles with angular frequency Ω_f, and find that there are stable orbits inclined at an angle θ to the fundamental plane. For $\Omega_f/\Omega_c \ll 1$, they derive the approximate relation

$$\tan\theta \approx 2\frac{\Omega_f}{\Omega_c}\left[1 - \left(\frac{\Omega_x}{\Omega_c}\right)^2 + \left(\frac{\Omega_f}{\Omega_c}\right)^2\right]^{-1}, \tag{7}$$

where Ω_x is an effective "spring constant" along the longest (x) axis and is smaller than the orbital frequency Ω_c. Assuming that the diffuse component is aligned perpendicular to the line of sight, and taking $\theta \approx 15°$, we have $\Omega_f/\Omega_c \leq 0.15$, where Ω_c is measured at the position of the ring. The ratio of the tumble frequency to the orbital frequency is smaller yet throughout the diffuse stellar component. The question remains as to whether such a slow rate of tumbling is consistent with the value of v/σ observed in the diffuse component.

Richstone and Potter (1982) and Schwarzschild (1982) have addressed this question, constructing models of stationary prolate and slowly tumbling triaxial galaxies and maximizing the stellar streaming through the figure of the galaxy. For their prolate, logarithmic potential, Richstone and Potter find a maximum v/σ of 0.075, while in his triaxial galaxy Schwarzschild finds a maximum of 0.4. Since we observe a much larger value of v/σ, we conclude that the diffuse stellar component cannot be a nearly prolate system tumbling at a rate for which the ring is in an equilibrium configuration. It remains possible that the ring might be stabilized by a slowly tumbling system, more nearly oblate than the model studied by Schwarzschild, since more nearly oblate systems permit larger value of v/σ. However, once one has found a model sufficiently oblate to account for the observed v/σ, one must still ascertain whether it permits equilibrium orbits at the observed inclination of the ring.

Throughout this subsection we have implicitly assumed that the potential in which the ring orbits has the same shape and tumbles with the same frequency as that part of the potential generated by the diffuse stellar component. We have not considered the possibility that the dark matter in the halo of NGC 4650A might have a very different configuration from that observed in the diffuse component. If the dark matter were triaxial or prolate and slowly rotating, the ring might be stable whatever the shape of the central component.

V. SUMMARY

The rotation observed in the diffuse stellar component of NGC 4650A is consistent with a range of models, with stationary oblate geometries at one extreme and rapidly tumbling prolate geometries at the other. Somewhere along this continuum there may exist a triaxial configuration, more oblate than the one studied by Schwarzschild, for which the ring would be stable. However, if strictly prolate or strictly oblate, the ring is unstable to differential precession and will settle into a plane more nearly perpendicular to the short axis of the diffuse component.

While the data for NGC 4650A taken alone do not permit discrimination between the oblate and prolate hypotheses, it is important to note that in all three cases where spindle-like galaxies have had rotation measured in the diffuse stellar component (NGC 2685, NGC 4650A, and A0136−0801), one observes $v/\sigma \geq 1$. If, as rotation is measured in the diffuse components in similar systems, one continues to find $v/\sigma \geq 1$, one may rule out the possibility that all of these systems are prolate, since one would occasionally expect to find the rotation axis oriented along or near the line of sight.

We wish to thank J. Fordham and K. Shortridge for their invaluable help in the course of the observing. It is our pleasure to acknowledge stimulating and enlightening conversations with R. Durisen, D. Richstone, and J. Tohline.

APPENDIX A

THE VELOCITY PROFILE OF THE GASEOUS COMPONENT

Figure 4 shows velocities measured on the plates obtained at CTIO.

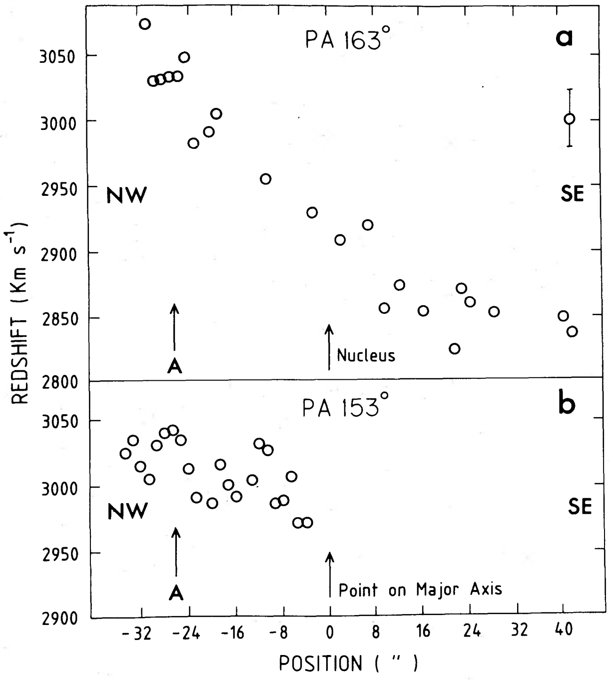

FIG. 4.—(*a*) Velocities of the ionized gas from the CTIO spectra: Average of the measures made on [O II] λ3727 (spectrum 1138) and Hα (spectrum 1150). The slit was oriented at P.A. 163°, passing through the nucleus (see Fig. 1). (*b*) Velocities for P.A. 153°. The slit crossed the diffuse component 5″.5 NE of nucleus (see Fig. 1). In both panels, A denotes the location of the point where the two slit positions crossed.

REFERENCES

Arp, H., and Madore, B. M. 1983, *Catalogue of Southern Peculiar Galaxies and Associations* (Toronto: Clarke-Irwin), in press.

Bertola, F., and Galletta, G. 1978, *Ap. J.* (*Letters*), **226**, L115.

Boksenberg, A. 1978, *Optical Telescopes of the Future: Conference Proceedings of December 1977* (Geneva: European Southern Observatory).

Binney, J., and de Vaucouleurs, G. 1981, *M.N.R.A.S.*, **194**, 679.

Burbidge, E. M., and Burbidge, G. B. 1959, *Ap. J.*, **129**, 271.

Davies, R. L., Efstathiou, G., Fall, S. M., Illingworth, G., and Schechter, P. L. 1983, *Ap. J.*, **266**, 41.

Freeman, K. C. 1970, *Ap. J.*, **160**, 811.

Gunn, J. E. 1979, in *Active Galactic Nuclei*, ed. C. Hazard and S. Mitton (Cambridge: Cambridge University Press), p. 213.

Hawarden, T. G., Elson, R. A. W., Longmore, A. J., Tritton, S. B., and Corwin, H. G. 1981, *M.N.R.A.S.*, **196**, 747.

Heisler, J., Merritt, D., and Schwarzschild, M. 1982, *Ap. J.*, **258**, 490.

Kotanyi, C. G., and Ekers, R. D. 1979, *Astr. Ap. Letters*, **73**, L1.

Lauberts, A. 1982, *The ESO/Uppsala Survey of the ESO* (*B*) *Atlas* (Garching: European Southern Observatory).

Laustsen, S., and West, R. M. 1980, *J. Ap. Astr.*, **1**, 177.

Miller, R. H., and Smith, B. F. 1979, *Ap. J.*, **227**, 785.

Richstone, D. O., and Potter, M. D. 1982, *Nature*, **298**, 728.

Sandage, A. R. 1961, *The Hubble Atlas of Galaxies* (Washington: Carnegie Institution of Washington).

Sargent, W. L. W., Schechter, P. L., Boksenberg, A., and Shortridge, K. 1977, *Ap. J.*, **212**, 326.

Schechter, P. L., and Gunn, J. E. 1978, *A.J.*, **83**, 1360.

Schwarzschild, M. 1982, *Ap. J.*, **263**, 599.

Sérsic, J. L. 1967, *Zs. Ap.*, **67**, 306.

Steiman-Cameron, T. Y., and Durisen, R. N. 1982, *Ap. J.* (*Letters*), **263**, L51.

Tohline, J. E., and Durisen, R. H. 1982, *Ap. J.*, **257**, 94.

Tohline, J. E., Simonson, G. F., and Caldwell, N. 1982, *Ap. J.*, **252**, 92.

van Albada, T. S., Kotanyi, C. G., and Schwarzschild, M. 1982, *M.N.R.A.S.*, **198**, 303.

van der Kruit, P. C., and Shostak, G. S. 1982, in *IAU Symposium 100, The Internal Kinematics and Dynamics of Galaxies*, ed. E. Athanassoula (Dordrecht: Reidel), p. 69.

Whitmore, B. C., and Kirshner, R. P. 1981, *Ap. J.*, **250**, 43.

Whitmore, B. C., Schweizer, F., and Rubin, V. C. 1982, *Bull. AAS*, **14**, 643.

Zwicky, F. 1967, *Adv. Astr. Ap.*, **5**, 333.

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