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THE DYNAMICS OF GALACTIC BULGES: NGC 7814 AND NGC 4594

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RESUMEN. Se han construido modelos estacionarios, internamente consistentes y axi-simétricos con integrales de energía y momentum angular, de los esferoides centrales de las galaxias NGC 7814 y NGC 4594 cuyos discos se observan aproximadamente de canto. Los modelos representan con exactitud observaciones de la distribución bi-dimensional de la brillantez superficial y observaciones kinemáticas asumiéndose que M/L es constante. Los modelos demuestran que todos los datos disponibles de esos esferoides son consistentes con la conclusión que los esferoides son isotrópicos y oblongados en los cuales el achatamiento se debe principalmente a la rotación pero con una pequeña contribución del disco. Valores M/L son derivados para NGC 7814 y NGC 4594 y se encuentran de acuerdo con valores receintémente observados en galaxias elípticas.

ABSTRACT. Stationary, self-consistent axisymmetric rotating models with energy and angular momentum integrals have been constructed for the bulges of the near edge-on disk galaxies NGC 7814 and NGC 4594. The models are capable of accurately fitting the observed kinematics with an assumption of constant M/L. The models demonstrate that all the available data on these two bulges are consistent with their being isotropic oblate spheroids in which the flattening is due mostly to rotation but with a small contribution from the disk. M/L values are derived for NGC 7814 and NGC 4594 and found to be consistent with recently observed values for elliptical galaxies.

I. INTRODUCTION

It is now clear that significant dynamical differences exist between bright elliptical galaxies and the bulges of disk galaxies (eg. Illingworth, 1977, Schechter and Gunn, 1979; Kormendy and Illingworth, 1982, hereafter KI; Illingworth and Schechter, 1982; Davies and Illingworth, 1983). From Binney's (1978, 1980) tensor virial models in the $V/\sigma \sim \epsilon$ plane, it seems that the bright ellipticals are flattened mainly by their anisotropic velocity dispersions. On the other hand, the bulges are well represented by rotationally flattened oblate models with nearly isotropic velocity dispersions. This important result came from using only characteristic values of the rotation, the velocity dispersion and the flattening: detailed information on the radial variations of all these quantities was not available at that time.

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For several bulges, we now have available detailed surface photometry and the two-dimensional distribution of rotational velocity and velocity dispersion. These data provide a more stringent constraint on the internal dynamics of bulges than do the $V/\sigma \sim \epsilon$ data alone. It is now worth making detailed self-consistent stellar dynamical models for bulges, and then comparing the predicted and observed light distributions and kinematics, to see if the internal dynamics of the bulges are adequately understood.

Our purpose in this paper is to show that the detailed two-dimensional photometric and kinematic properties of spheroidal galactic bulges can be adequately represented by simple rotationally flattened oblate stellar dynamical models. Also, the disk of a disk galaxy can provide a significant contribution to the flattening of the bulge, as suggested by Freeman (1977) and Monet et al. (1981). We include the disk in our models, in order to estimate its importance for the dynamics of the bulge.

The models are based on a distribution function with two integrals of motion, E the total energy per unit mass, and J, the angular momentum per unit mass about the axis of rotation, i.e.

$$f(E,J) = \alpha[\exp(-\beta E)-\exp(-\beta E_0)] \exp(\gamma J)$$

where $E \leq E_0$ = constant and α, β, and γ are also constants. The density ρ at any point is found by integrating f(E,J) over velocity space. Self-consistency for the bulge is achieved by solving Poisson's equation for the total gravitational potential, U, i.e.

$$\nabla^2 U(r,\theta) = 4\pi G\rho(r,\theta)$$

where G is the gravitational constant.

As mentioned above the disk of a galaxy also provides a significant contribution to the total (i.e. bulge + disk) potential, and should not be ignored. For simplicity, the disk potential is represented as a static, externally imposed potential.

In view of their analytic simplicity, the disk models of Miyamoto and Nagai (1975) were used and in cylindrical coordinates (R,z) are given by,

$$U_d(R,z) = \frac{GM_d}{\{R^2 + [a+(z^2+b^2)^{\frac{1}{2}}]^2\}^{\frac{1}{2}}}$$

where a and b are the disk scale lengths in the equatorial and vertical directions respectively. M_d is the mass of the disk. The effect of a massive galactic halo is assumed unimportant to the most observable properties of the bulge.

The disk potential field satisfies Laplace's equation outside the disk and Poisson's equation within, i.e.

$$\nabla^2 U_d = 0 \qquad \text{outside the disk}$$

$$\nabla^2 U_d = 4\pi G\rho_d \quad \text{inside the disk}$$

Using appropriate scale factors, the above equations were made dimensionless (for details see Jarvis and Freeman 1984). The models in dimensionless space require five free parameters to uniquely specify them i.e. W_b^o, γ, a, b, and Q. The first two, the dimensionless central bulge potential and the rotation parameter γ define the bulge. The disk scale lengths a and b, together with $Q = \mu_b M_d/M_b$ define the disk. M_d and M_b are the masses of the disk and bulge respectively. μ_b is defined by $M_b = \rho_b^o r_c^3 \mu_b$ where r_c is the bulge core radius and ρ_b^o is the central bulge density. A numerical check on the models was made by showing that the stellar hydrodynamical equations were satisfied at all grid points in the model.

II. COMPARISON: MODELS WITH OBSERVATION

To test the dynamical bulge models we now apply these to two early type edge-on disk galaxies: NGC 7814 and NGC 4594. Using the observed two-dimensional surface brightness distribution for each of the two galaxies, our aim was to see whether our models were capable of accurately reproducing both the observed two-dimensional light distribution and the observed kinematical properties of each bulge. We first examined NGC 7814. In the absence of any quantitative data concerning the scale lengths a and b of the disk, a scale height ratio of b/a = 0.1 was chosen as reasonable from examination of a direct plate. Similarly, the mass ratio M_d/M_b was adopted to be 0.25. The gross properties of the models are dominated by changes in W_b^o and γ only, i.e. errors in a, b and M_d/M_b produce only second order changes in the overall properties of the models.

TABLE 1

NGC	W_b^o	γ	M_d/M_b	a	b	r_t	W_d^o	$\frac{\lambda\Sigma_o}{\sigma_o'^2}$	r_c''	I_V^o mag.arcsec^{-2}
7814	-8.5	0.200	0.25	10	1	45.4	-1.01	18.78	2.4	13.08
4594	-8.5	0.125	0.25	10	1	67.7	-1.01	18.21	8.5	13.09

Using the above disk parameters, a model was constructed which is in excellent agreement with the observed surface brightness distribution in V; its parameters are given in Table 1. The two-dimensional fit of the projected model to the observed surface brightness distribution is shown in Figure 1. Due to the observational symmetry of the bulge, the data have been reflected and averaged about the minor axis to improve the signal-to-noise ratio. To extend the range of the fit, the outer regions have been smoothed by a two-dimensional Gaussian filter with half-widths from 1"x1" for the fifth faintest isophote (21.9 mag.arcsec^{-2}) to 3"x3" for the faintest isophote (23.91 mag.arcsec^{-2}). The isophotes are drawn in intervals of 0.50 mag.arcsec^{-2} in V with the faintest isophote in the lower panel at 23.91 mag.arcsec^{-2}. It can be seen from Figure 1 that the model is in excellent agreement with the observed two-dimensional light distribution in V to the limit of the photometry. However, this alone is insufficient to establish the models as being truly representative of the current dynamical state of this galactic bulge. For example, in earlier attempts (e.g. Prendergast and Tomer, 1970; Wilson, 1975) to fit rotating models to elliptical galaxies, the model fits to the observed brightness distributions were fairly successful. However, subsequent kinematical observations (e.g., Illingworth, 1977) indicated that these models possessed at least twice as much net rotation as observed. Clearly then, the models must also be simultaneously consistent with the observed kinematics, since, as experience has shown, the kinematical data places such severe constraints on the models.

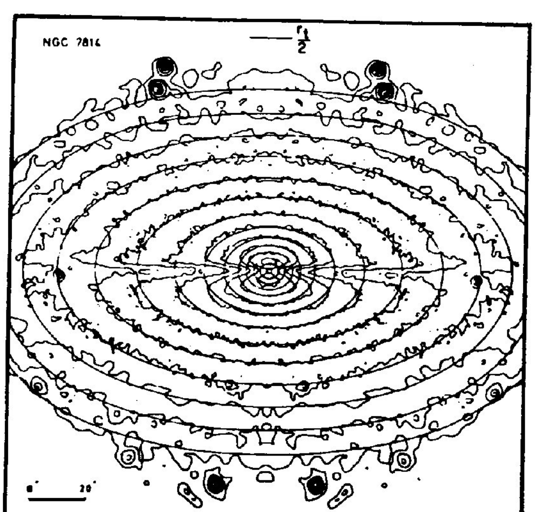

FIGURE 1

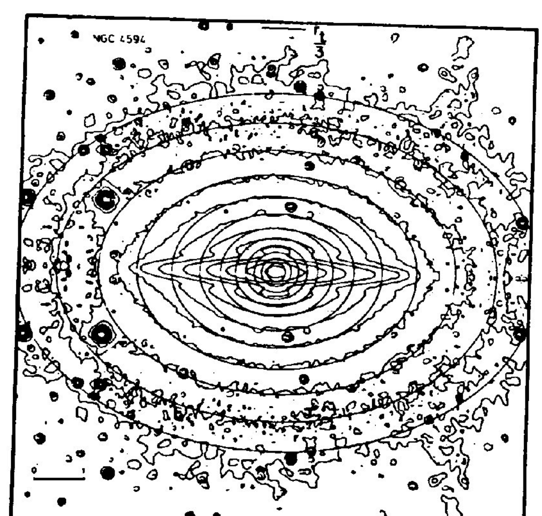

FIGURE 3

The kinematical data for NGC 7814 are taken from KI. They have mapped the spatial distribution of velocity dispersion and rotation velocity in the bulge along cuts 4", 12" and 18" above and parallel to the disk, while the cuts perpendicular to the disk were at 20" and 40" from the minor axis. The minor axis was also observed. To match the model data, there is only one degree of scaling allowed (which is equivalent to choosing M/L), e.g. the central velocity dispersion σ_0 or the maximum rotation velocity on the major axis $V_m(0)$, but not both independently. There is no freedom to choose a lengthscale, since this is already fixed from the model fit to the surface photometry.

Therefore, using $(\sigma_0)_{mod}$= 160 km.s^{-1} for the adopted central velocity dispersion of the model, the value of $V_m(0)_{mod}$ for the major axis is 125 km.s^{-1}, since $(V_m(0)/\sigma_0)_{mod}$ = 0.78. Since the rotation curve on the major axis is not directly observable because of the disk, KI computed a value of V_m corrected to z=0" i.e., $V_m(0)_{obs}$. They found $V_m(0)_{obs}$=123±12 km.s^{-1}. Therefore, using the velocity dispersion determined above from the minor axis cut gives $(V_m(0)/\sigma_0)_{obs}$ = 0.77±0.09. This is to be compared with the same quantity derived from the adopted model: $(V_m(0)/\sigma_0)_{mod}$=0.78, in good agreement with observation. The maximum ellipticity ε_{max} derived from the model was 0.44. Figure 2 compares the model kinematical distributions with the observed kinematical distributions. It is clear that the agreement is excellent within the observational uncertainties. The only systematic deviations of the models from the data appear in the outermost determination of the velocity for the 4", 12" and 18" parallel cuts. In all cases, the velocity of the outermost point is above that predicted by the model: however, KI give low weight to these points. KI find $V_m(0)/\sigma$=0.85±0.10 when using a mean dispersion derived from averaging the dispersion interior to half the effective radius (de Vaucouleurs, 1959) and excluding the central 1.4". The difference between the value of $V_m(0)/\sigma$ derived from KI and that derived from this work is in the correct sense, since their method of choosing σ will for most galaxies yield a lower value than that used here. However the ellipticities are in good agreement, although measured slightly differently.

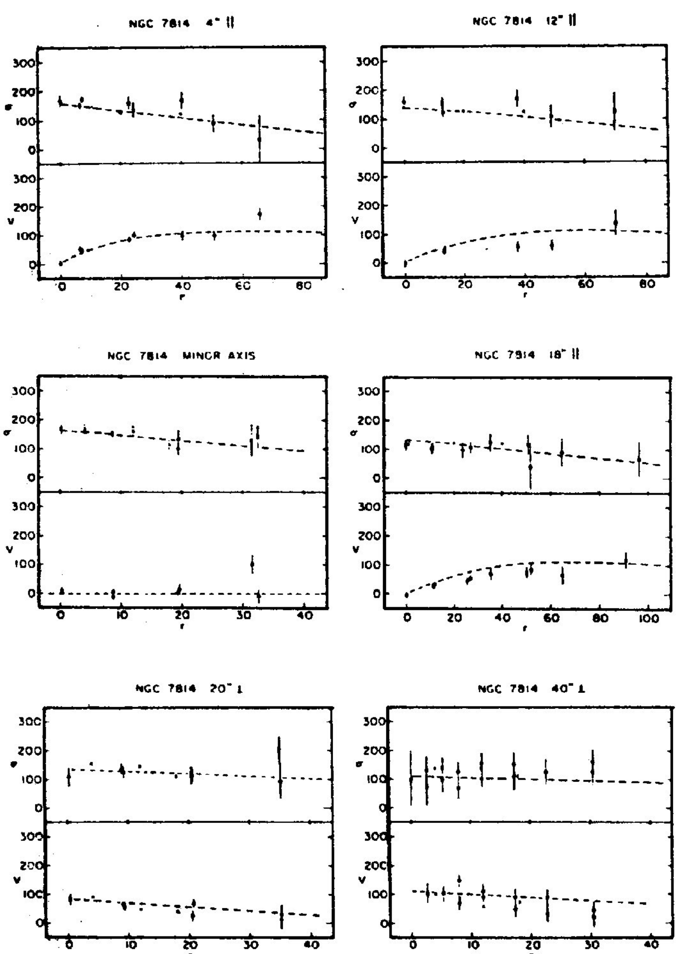

FIGURE 2

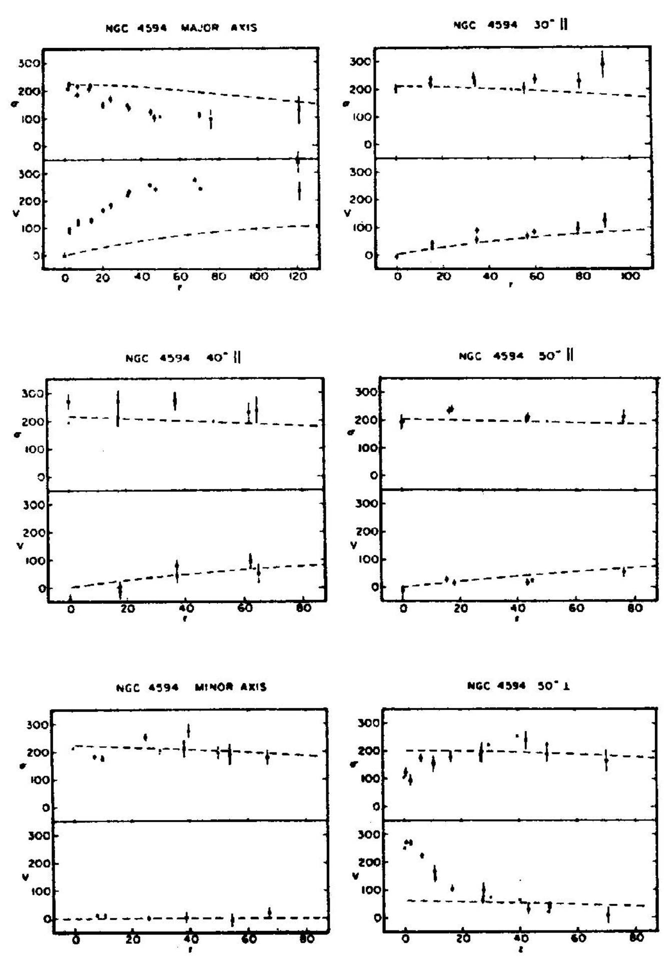

FIGURE 4

The observed mass-to-light ratio $(M/L)_V$, from the model assumptions in solar units is:

$$(M/L)_V = 0.0109 \; \frac{\lambda^{\Sigma_o}}{\sigma_o'^2} \cdot \frac{\sigma_o^{*2}}{I_V^o \; r_c''} \cdot \frac{1}{D}$$

where Σ_o is the dimensionless model central surface density,
σ_o is the observed central velocity dispersion in $km.s^{-1}$,
σ_o' is the dimensionless model central velocity dispersion,
r_c'' is the observed core radius in arc seconds,
I_V^o is the central surface brightness measured in units of one 20th mag star $arcsec^{-2}$,
D is the distance in Mpc,
and λ is a model-dependent parameter (see JF: cf. Wilson, 1975).

Assuming a distance of $25h^{-1}$ Mpc (KI), a core radius of 2.4" (291pc) and $\sigma_o = 160$ $km.s^{-1}$, the model gives a mass-to-light ratio in V of 8.5h (where $h=H/50$ $km.s^{-1}.Mpc^{-1}$) from equation 1. No correction for extinction has been made. This value is consistent with observations by Faber and Jackson (1976) who find a mean of seven for the observed mass-to-light ratio in the nuclear regions of elliptical galaxies. It should be noted however, that this value is derived from observations near the center of the galaxy and may not be the same as the ratio of total mass to total luminosity. On the other hand, it has been seen that a very satisfactory fit to the surface photometry and kinematics was possible using a constant M/L.

As a second example of the application of this model to real galaxies we examine the near edge-on SA galaxy NGC 4594. For this study, the surface photometry was derived from a 2^h33^m exposure using a 103a-D+GG495 plate-filter combination. Again, using the same disk parameters as before and the fitting techniques detailed above, a model was construed to fit the observed light distribution of NGC 4594 in the V passband; the final parameters are given in Table 1. The fit of the model to the two-dimensional light distribution is shown in Figure 3 after the northern and southern halves have been averaged and reflected about the major axis. The faintest isophote (23.70 $mag.arcsec^{-2}$) was plotted after smoothing with a two-dimensional Gaussian filter of halfwidth 6". The isophote spacing is 0.5 magnitudes. Again it can be seen that the overall two-dimensional fit is in excellent agreement with the observations.

As before, once a suitable model had been found to fit the observed light distribution, a comparison of the model's kinematical properties with those observed was made. Again, the data used here is taken from KI. From this data the central velocity dispersion was found to be $\sigma_o=225\pm15 km.s^{-1}$. Hence, using $V_m(0)_{obs} = 130\pm24$ $km.s^{-1}$ from KI, the observed value of $V_m(0)/\sigma_o$ is 0.58 ± 0.11. The corresponding model value is 0.57, again in excellent agreement and well within the observational formal error of 0.11 for $V_m(0)/\sigma_o$. The model has an ellipticity of $\varepsilon_{max} = 0.32$. When consideration for both the errors and the different methods of measurement is made, the values of $V_m(0)/\sigma_o$ and ε are in good agreement with those of KI. They found $V_m(0)/\sigma = 0.63\pm0.12$ and $\varepsilon = 0.37\pm0.08$, both of which may have been slightly overestimated (KI, private communication). Figure 4 shows the model kinematical distributions compared to those observed by KI. The dashed lines show the model predictions with σ_o as the free parameter scaled to 225 $km.s^{-1}$. The agreement between the model and observed kinematics is again excellent. The velocity and dispersion profiles on the major axis are clearly disk dominated, as shown by the large excess of observed rotational velocity over the model and the lower dispersion of the "colder" disk. A determination of M/L can also be made for NGC 4594 from the photometry and the adopted model. Assuming a distance of $17.9h^{-1}$ Mpc, and a core radius of 8.5" (738 pc), the mass-to-light ratio $(M/L)_V$ from equation 1 is 3.6h. Faber et al. (1977) find $(M/L)_B<3$ to 4 for the spheroidal component alone from rotational motions of HI in the disk and optical absorption line velocities: their adopted distance is 18.6 Mpc. See Faber et al. (1977) for discussion of earlier M/L estimates for this galaxy. From the kinematics of HII regions in NGC 4594, Schweizer (1978) found that the integrated $(M/L)_V$ ratio increases with radius to about 3 at the radius corresponding to the outermost points shown in our Figure 3. The agreement of these three independent estimates for M/L is very good.

III. THE V/σ∿ε PLANE

It has been shown by Binney (1980), Illingworth and Schechter (1982), KI and others that the dimensionless, distance independent quantity $V_m(0)/\sigma_0$, the ratio of the peak rotation velocity on the major axis to the central line-of-sight velocity dispersion, quantifies the relative importance of rotation in galactic bulges. It does this by measuring the fraction of dynamical support offered by ordered motion (rotation) to random motion (dispersion). In the interest of investigating whether bulges of disk galaxies are in general rotationally flattened, it is useful to measure this quantity in as many bulges as possible. Figure 5 shows the results from computing two types of models. The first shown by region 1 consists of a grid of models in which the bulge is rotationally flattened with no disk. Region 2 is defined by the locus of models with a disk. The disk-to-bulge mass ratio was kept constant with $M_d/M_b = 0.25$. The disk scale lengths were also held constant at a = 10 and b = 1. Both regions were computed by changing W_b^o and γ only. Region 2 is the relevant region to use here since both the models fitted above included a disk with these same parameters. With the generation of regions 1 and 2, the data from Table 2 were plotted in the $V_m(0)/\sigma_0 \sim \varepsilon_{max}$ plane and compared with the theoretical predictions to gauge the importance of rotational support and flattening in real bulges. The data from Table 2 were further supplemented by a sample of eight galaxies taken from KI and Davies and Illingworth (1983) and plotted with the two galaxies from this work.

TABLE 2

Galaxy	V_m (km.s^{-1})	$V_m(0)$ (km.s^{-1})	σ_0 (km.s^{-1})	$\left(\frac{V_m(0)}{\sigma_0}\right)_{obs}$	$\left(\frac{V_m(0)}{\sigma_0}\right)_{mod}$	$\left(\frac{V_m(0)}{\sigma_0}\right)^*$	ε_{max}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 7814	83±14	123±12	160±10	0.77±0.09	0.78	0.95	0.44
NGC 4594	108±19	130±24	225±15	0.58±0.11	0.57	1.02	0.32

The first point to note is the excellent agreement between the rotating bulge models defining Region 1 and the oblate model predictions of Binney, even though our Region 1 is defined by the central velocity dispersion and not a global value. Observationally, this may be complicated in some bulges which show significant velocity dispersion gradients. By way of illustration, KI quoted a mean dispersion of 144±10 km.s^{-1} for NGC 7814 compared with a central dispersion of 167±18 km.s^{-1}. If the central dispersion is adopted, then $V_m(0)/\sigma_0 = 0.74\pm0.11$, compared to $V_m(0)/\sigma_0 = 0.85\pm0.10$, a difference of 13 per cent. Also, the value of $V_m(0)/\sigma_0$ derived from the NGC 4594 model (open circle) is in good agreement with the observed value (filled circle). The model value of $V_m(0)/\sigma_0$ falls well within the error associated with the observed value. The agreement for NGC 7814 is similar; the model value also lies within the associated observed value.

Figure 5 also clearly demonstrates the importance of the disk to the global dynamical properties of the bulge as suggested by Freeman (1977 and 1979) and Monet, Richstone and Schechter (1981). Eight of the ten bulges measured lie in or near Region 2, defined by disk models. Figure 5 illustrates that the measured bulges are displaced from the oblate rotationally flattened region 1, in the sense expected from the influence of the disk. However, the fact that they lie so nicely in region 2 should not be taken too seriously in every case, because our value $M_d/M_b = 0.25$ used to calculate region 2 is probably an underestimate for some of these systems. The two most discrepant galaxies NGC 224 and NGC 3031 are also the least edge-on systems in the sample. Whether this is a coincidence or not is unclear since varying the observed inclination of the bulge drives the models along the oblate line (Illingworth, 1977). One possible explanation is that if the bulge is optically thin then the disk must be contributing some light at every position in the bulge which would tend to lead to an overestimate of $V_m(o)/\sigma_0$ for the bulge.

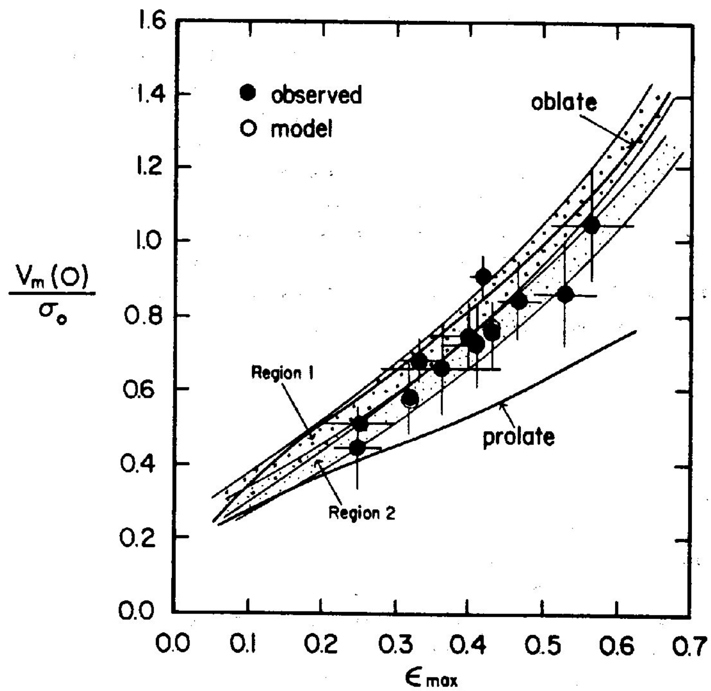

FIGURE 5

IV. CONCLUSIONS

It has been shown observationally that the bulges studied in this and KI's sample rotate at least as rapidly as required by the oblate-spheroid models in which the observed flattening is due almost entirely to rotation. Here, it has also been demonstrated that the observed light distribution and the detailed kinematical properties are well approximated by a distribution function with only two isolating integrals of motion, the total energy per unit mass and the angular momentum per unit mass about the z-direction. The models so constructed are oblate and flattened mainly by rotation, but with a small contribution (typically $\sim$ 10%) due to the disk, unlike the brighter elliptical galaxies. The models were also shown to reproduce accurately the observed internal kinematics within the observational errors over the entire spatial range observed.

Finally, the models clearly demonstrate the importance of the galactic disk to the global dynamical properties of the bulge. The observations also suggest that the disk has a significant effect on the bulge, because the observed bulges lie in Region 2 of Figure 5. In the absence of a disk, we would expect a rotating oblate spheroid with an isotropic velocity distribution (in V_R,V_Z) to lie in Region 1 of Figure 5. We note that departures from axisymmetry or velocity isotropy could give a similar displacement from Region 1 to Region 2. However, the points in Figure 5 all lie fairly close to Region 2; this argues for a common cause for the displacement, which we believe favors the effect of the disk as the most likely explanation. Consideration of the influence of the disk on the bulge may hopefully lead to some insight into the observed scatter of real bulges about the isotropic line in the $V/\sigma \sim \varepsilon$ diagram. For example can the departure from the oblate line be related to the observed bulge-to-disk mass ratio? These and other questions require further study.

Our models worked very well for the two spheroidal-type bulges of NGC 7814 and NGC 4594 and we would argue that the dynamics of these bulges are now fairly well understood. While our simple distribution function is probably not precisely correct, it obviously represents these systems very well. Why the distribution function has this particular form is a deeper question which we will not attempt to discuss here.

We would not claim that the models will work equally well for other kinds of bulges. For example the velocity dispersion in the outer parts of the galactic bulge is highly anisotropic ($\sigma_R >> \sigma_Z$: Wooley, 1978; Pier, 1983; Ratnatunga and Freeman, 1984). This anisotropy means that there are more than two effective integrals of the motion, so more elaborate models are certainly needed to model the galactic bulge. Our models will also not work for the box or peanut shaped bulges (like NGC 128, NGC 4565): these show cylindrical rotation, unlike the spheroidal rotation fields seen in Figures 2 and 4 (see Kormendy and Illingworth, 1982). Cylindrical rotation does not necessarily imply more than two integrals of the motion: however, a different distribution function is clearly required to represent this kind of bulge. Further, the box shaped bulges are usually (but not always) found in systems with a large disk-to-bulge mass ratio, so the effect of the disk is yet more significant for these bulges than it is for the systems that we have discussed here. These types of bulges require further work. The complete version of this paper has been submitted to *The Astrophysical Journal.*

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