THE ASTRONOMICAL JOURNAL VOLUME 104, NUMBER 4 OCTOBER 1992

THE REMARKABLE TWISTED DISK OF NGC 4753 AND THE SHAPES OF GALACTIC HALOS

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Received 9 May 1991; revised 18 June 1992

ABSTRACT

The complex dust lanes in the S0 galaxy NGC 4753 are shown to be consistent with a disk that is strongly twisted by differential precession. Yet another peculiar S0 can therefore be explained as the result of an accretion event. An evolving disk model is fitted to the observed dust distribution. This disk is inclined by 15° relative to the galaxy's equatorial plane and twisted such that its line of nodes changes smoothly by 3.8π over a factor of seven in radius. The model shows excellent agreement between increased line-of-sight path lengths through the disk and the observed dust lanes. A nodal precession rate proportional to r^{-1} matches the observations with considerable accuracy. The model indicates that most of the galaxy's mass is unseen, is nearly spherically distributed, and has a nearly scale-free spatial distribution. The ellipticity of the total galactic mass distribution must be constant to within 20% over the radial extent of the twisted disk—a conclusion which may significantly constrain galaxy formation mechanisms. If the disk and the main body of NGC 4753 rotate in the same direction, then the sense of the twist implies an oblate galactic mass distribution. The flattening of the halo and the age of the accretion event cannot be determined independently, but physical arguments imply that the shape of the total mass distribution is between ~E0.1 and E1.6.

1. INTRODUCTION

One of the most fundamental physical attributes of a galaxy is the three-dimensional shape of its mass components. However, remarkably little is known about the geometry of dark halos (see Kormendy 1988 for a review), even though evidence for the existence of dark matter is now compelling. A useful diagnostic for some systems is provided by disks which lie outside the symmetry plane of the galactic light distribution. For example, Schweizer, *et al.* (1983) and Whitmore *et al.* (1987) compared the rotation curves of the polar rings and the equatorial disks of three polar-ring galaxies. To within the observational error, the rotation curves in the orthogonal directions were indistinguishable, indicating that the total galactic mass distribution (dark halo plus luminous matter) is "more nearly spherical than flat." For the past decade, two of us have undertaken a systematic theoretical study of galactic gas disks in unusual orientations (cf. Steiman-Cameron & Durisen 1982, 1984, 1988, 1990; Steiman-Cameron 1984, 1991, and references therein). Our motivation was the realization that such disks could be used as dynamical probes of the three-dimensional mass distribution. For instance, time-dependent differential precession can provide a large and distinctive signal arising solely from quadrupole and higher moments of the total mass distribution. NGC 4753 provides an ideal opportunity to apply this kind of analysis.

NGC 4753 is an early-type galaxy with a very prominent but complicated dust distribution (Fig. 1) (Plate 98). It is illustrated in the *Hubble Atlas* (Sandage 1961), where it is classified S0 pec because its "underlying luminosity distribution would resemble an $S0_1$." Large rotational velocities, $v > 250\ \mathrm{km\ s^{-1}}$ (Chromey 1973), support the S0 interpretation. The RC2 (de Vaucouleurs *et al.* 1976) goes further and calls it an I0. One of us (J. K.) obtained an image with the Canada–France–Hawaii Telescope (CFHT) as part of a study of the cores and dust properties of early-type galaxies (e.g., Kormendy 1987; Kormendy & Stauffer 1987). An unsharped-masked version of this image suggested that the dust lies in a disk wrapped several times around the center. In this paper, we show that an inclined disk twisted by differential precession fits the observed dust lanes very well. This demystifies what previously looked like a complicated galaxy and shows that yet another apparently peculiar object can be understood as an otherwise normal galaxy which has experienced an accretion event.

The properties of the twisted disk constrain the shape of

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the total mass distribution of NGC 4753 over a large range in radius. Despite the flattening of the observed light distribution, our model implies that the total mass distribution is no flatter than ~E1.6 and may be as spherical as E0.1, that the degree of flattening is constant with radius to within twenty percent, and that the total gravitational potential is scale-free to a good approximation.

2. OBSERVATIONS

Figure 1 shows a 1200 s *V*-band image obtained at the Cassegrain focus of the CFHT. The detector was an RCA CCD with 316×498, 30 μm pixels; read noise ~71 electrons pixel^{-1} (Walker *et al.* 1984). The scale is 0".215 pixel^{-1}. Since the CCD field of view is only 68"×107" (the "oval" in Fig. 1 measures 58"×84"), we also show in Fig. 2 (Plate 99) a wider-field photograph kindly provided by A. R. Sandage. The CCD image has a seeing $\sigma_*=0''.37$ (Gaussian dispersion of a star profile). Instrumental reduction was carried out in the usual way.

The image in Fig. 1 was "unsharp masked" by fitting elliptical isophotes to the intensities, constructing a synthetic image with elliptical isophotes and the derived radial brightness profile, and dividing this into the original. The radial brightness profile and the isophote ellipticities are affected by the dust and therefore do not accurately represent the stellar distribution underlying the dust. However, the synthetic image is smooth and close to correct, so unsharp masking removes most of the radial brightness variation without affecting the small-scale structure we are trying to understand. Figure 1 allows us to show this structure at relatively high contrast over a large radius range.

Figure 1 immediately suggests an explanation for the dust distribution. It looks like a semitransparent sheet wrapped several times around the center, if the nearly horizontal dust arcs are caustics where the sheet is seen edge-on. The rest of this paper is an attempt to model such a sheet, not only as it is seen now but through its evolution since the accretion event.

The physical parameters of the model depend somewhat on the scale of the image. Here we adopt a distance of 8.7 Mpc from a distance modulus of 29.7±0.4 determined by Buta *et al.* (1985) using published estimates and the light curve of supernova SN 1983*g*. For this assumed distance, 10" corresponds to 0.42 kpc. Implications of uncertainties in the distance to NGC 4753 are discussed in Sec. *3.3*.

3. DISK STRUCTURE AND PHYSICAL PARAMETERS OF NGC 4753

3.1 Outline

To interpret the structure of an accreted disk in the context of the host galaxy's geometry, we need to understand how a thin disk with arbitrary initial orientation evolves in the gravitational potential of a nonspherical galaxy. A detailed description of the evolution of nonplanar disks subject to both precessional and dissipative forces can be found in Steiman-Cameron & Durisen (1988, 1990; hereafter SCD1 and SCD2, respectively, and references therein; see also Tubbs 1980; Tohline, *et al.* 1982; Steiman-Cameron 1984, 1991; Habe & Ikeuchi 1985, 1988; Varnas 1986a,b; Christodoulou 1989, 1990). Numerical studies indicate that material accreted into the gravitational potential of a galaxy will smear out into an annular disk in a few orbital periods (Varnas 1986a; Rix & Katz 1991). The three-dimensional structure of the newly formed disk will then evolve on the longer precessional and dissipative time scales. Differential precession causes a smooth, continuous twist to develop. At the same time, dissipation within the twisted disk leads to changes in the inclination of the disk, transport of angular momentum, and inflow of material toward the center. Ultimately, the disk settles into a *preferred* orientation. Thereafter, the orientation remains fixed with respect to the galaxy, i.e., the disk no longer precesses. For static galactic potentials, preferred orientations are symmetry planes of the mass distributions (cf. Tohline & Durisen 1982; Durisen *et al.* 1983; Steiman-Cameron & Durisen 1982, 1984, and references therein). Self-gravity can complicate this process for sufficiently massive disks (cf. Hunter & Toomre 1969; Sparke 1984; Sparke & Casertano 1988). However, it appears to have been unimportant for the twisted disk of NGC 4753 (see Sec. *3.2*).

Numerical methods are generally required to follow the above process. However, analytic descriptions are possible for disks formed at small or moderate inclinations with respect to the equatorial plane of axisymmetric galaxies (SCD1, SCD2). In this case, dissipation causes the disk to settle towards the equatorial plane and inflow times are much longer than settling times. In what follows, the scale-free analytic solution of SCD2 is applied to NGC 4753.

The geometrical configuration of a disk at any time t can be described by the sizes and orientations of the annular Lagrangian mass elements of the disk. The size of a mass element is specified by its circular semimajor axis a. Its orientation is given by the inclination i measured with respect to the equatorial plane and by the longitude of its ascending node Ω. Considering only orbit-averaged forces, the time-dependent structure of a settling disk can be described in terms of the two dimensionless parameters $\aleph=(\tau_p/\tau_e)$ and $T=(t/\tau_p)$, where $\tau_p=2\pi/|\dot\Omega_p|$ is the precession period, $\dot\Omega_p$ is the nodal precession rate, $\tau_e=[(\nu/6)(d\dot\Omega_p/d_r)^2]^{-1/3}$ is the effective settling time, and ν is the effective coefficient of kinematic viscosity. As given by Eqs. (4a) and (4b) of SCD2, the structure of a disk which is initially planar with $(i,\Omega)=(i_0,0)$ at time $t=0$ is given by

$$i/i_0=\exp[-(\aleph T)^3], \tag{1a}$$

$$\Omega=\pm 2\pi T. \tag{1b}$$

The right-hand side of Eq. (1b) is negative for oblate galaxies and positive for prolate systems.

At any time t, the parameters $\aleph$ and T are completely defined by the precession rate and the coefficient of viscosity. The determination of $\aleph$ and T thus provides fundamental information about both the global distribution of matter in the host galaxy and the dissipative forces acting on the disk. In general, $\aleph$ and T are functions of radius.

3.2 Model Parameters

An axisymmetric, scale-free, logarithmic gravitational potential is used to model NGC 4753. As shown below, this potential provides an extremely good representation of NGC 4753 over the radial range of the twisted disk. A brief discussion of this potential can be found in the Appendix of SCD2 (see also Richstone 1980; Monet *et al.* 1981; Levison 1987). The scale-free potential has a flat rotation curve. Its isopotential surfaces are similar and concentric spheroids; isodensity surfaces of the galactic mass distribution are also similar and concentric. The isodensity surfaces are "dimpled" along the symmetry axis. However, for the degree of flattening described below these isophotes are well approximated by spheroids.

While the assumption of a constant circular velocity v_c over the radial range of interest for NGC 4753 is reasonable, the rotation curve has not been determined for $r \gtrsim 40''$. Chromey (1973) has measured an absorption-line rotation curve which rises linearly to ~ 300 km s^{-1} at 40″, with the western edge approaching and the eastern edge receding relative to the galaxy's center. The absorption-line rotation curve $v(r)$ is related to the circular-orbit rotation curve $v_c(r)$ by the equation for the "asymmetric drift," i.e., the first velocity moment of the collisionless Boltzmann equation, through the velocity dispersion σ and the unprojected density of stars contributing to the spectra (cf. Eq. [6-29] of Mihalas & Binney 1981; Binney & Tremaine 1987). Without data on the velocity dispersion profile, we cannot derive the circular velocity. Also, if the dust obscuration is optically thick along the line of sight, we do not integrate v through the whole galaxy. This tends to make the rotation curve look too linear; in the extreme case of an opaque disk, we would measure $v \propto r$. Accurate velocity (v and σ) data and kinematic modeling would both be required to derive the circular-orbit rotation curve. Here we assumed v_c=constant=300 km s^{-1}, and address later the implications of $v_c \neq$constant. The adopted value of v_c is consistent with H I observations of NGC 4753 (Richter 1991, private communication) and with the observations of Chromey.

In a scale-free axisymmetric galaxy of axial ratio c/a (a and c are equatorial and polar semiaxes of an isodensity surface, respectively), the precession rate for a circular orbit at radius r is (SCD2)

$$\dot{\Omega}_p = -(3v_c/4r)\eta \cos i, \tag{2}$$

where $\eta = (2/3)[1-(c/a)^2]/[2+(c/a)^2]$. Note that $\dot{\Omega}_p$ is negative for oblate galaxies ($c/a<1$) and positive for prolate systems ($c/a>1$).

The visual appearance of model disks generated for a range of $\aleph$ and T using Eqs. (1a) and (1b) were examined at various viewing orientations using a 3-D graphics workstation. Consistent with Eq. (2), the models assumed $T \propto r^{-1}$. Comparisons with observed dust lanes at radii interior to 45″ (Fig. 1) were made to determine the "best fit" values of these parameters, the range of acceptable values, and the orientation of the disk with respect to the observer. These models were then compared with the observations to a radius of 90″ (Fig. 2) to evaluate the goodness of fit over the entire range of the dust features.

Good agreement between models and observations were found only for a fairly narrow range of parameters, but within this range the agreement is remarkable. The dust lanes of NGC 4753 can be reproduced if they are interpreted as optical depth effects in a nearly edge-on twisted disk described by

$i_0 = 15° \pm 3°$,

$\aleph \leqslant 0.2$,

$T = (2.2 \pm 0.3) \times (r_0/r)$,

where r_0 is the physical radius corresponding to an angular radius of 13″. For a distance of 8.7 Mpc, r_0=0.55 kpc. The fit of the model to observations requires that the line of sight is inclined by $8° \pm 2°$ to the equatorial plane of the potential. If the stellar disk of NGC 4753 lies in this plane, then its angular momentum vector is inclined by $98° \pm 2°$ to the line-of-sight towards the south on the sky. The sense of precession, i.e., whether the line of nodes progresses or regresses, depends upon the geometry of the gravitational potential. The sense of twist of the dusty disk in NGC 4753 given by our fit is that expected from precession in an oblate halo, provided that the (yet undetermined) sense of orbital motion in the accreted disk is the same as that of the underlying stellar disk of NGC 4753.

The radial extent of the twisted disk model is $13'' \leqslant r \leqslant 90''$ (0.5 to 4 kpc at an assumed distance of 8.7 Mpc). While the accreted disk may extend to $r<r_0$, the optical images preclude a determination. The disk appears to extend to greater than 120″ (see below), however the orientation of the disk beyond $\sim 90''$ does not lead to well-defined dust lanes which serve to strongly constrain the disk's geometry. Over the range 13″–90″, the disk maintains a nearly constant inclination while twisting by 3.8π radians.

The excellent fit of the model to observations is shown in the plots of Figs. 3 and 4. These figures were generated for an $\aleph$=0 model (models with $\aleph \leqslant 0.2$ are virtually indistinguishable) assuming a disk surface density distribution $\propto r^{-1}$. This distribution was adopted strictly for illustrative purposes and plays no role in the model. The nonplanar structure of the disk together with the viewing orientation causes the projected path-length through the disk to vary with position. In the figures, lighter shades correspond to larger optical depths arising from increased line-of-sight path-lengths. We note that the geometric model and viewing orientation are very well determined and can be considered a good fit to the disk shape independent of the underlying physical model that this twisted structure arises from differential precession.

Figure 3 shows the CCD image of the inner disk together with the model disk extending in radius from 13″ to 45″. Figure 4 shows the galaxy at larger radii together with the dust structure predicted by the model out to 90″. In both figures, the model reproduces dust features remarkably well, even though only radii interior to 45″ were used to determine the fit. This testifies to the scale-free nature of

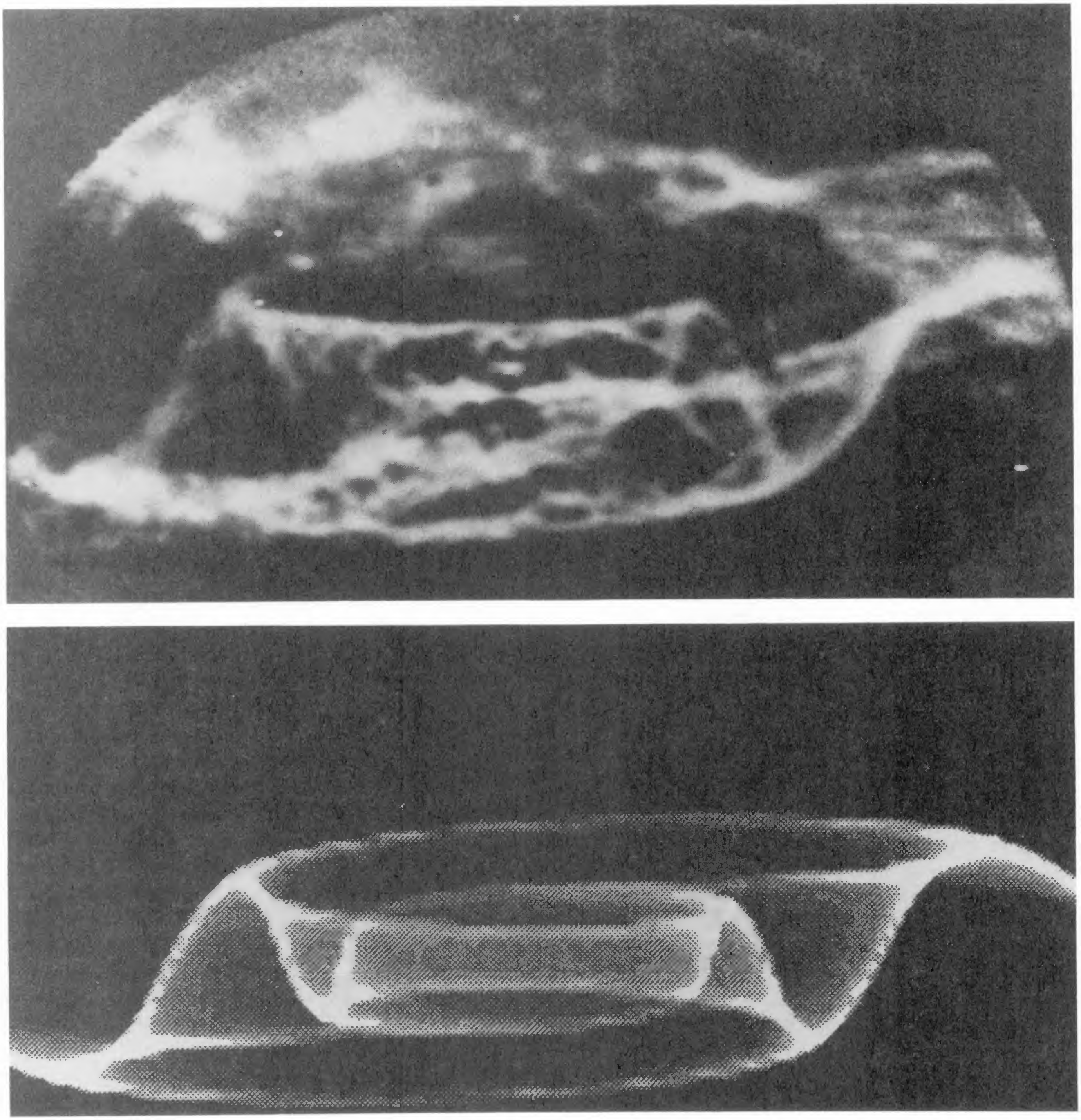

FIG. 3. Model fit to NGC 4753 over the radius range 13" to 45". Except for a linear feature extending from the lower left towards the upper right in the CCD image, there is extremely good agreement between the model and the dust lanes. The linear feature is consistent with a circular ring of enhanced dust obscuration within the disk.

the potential. The quality of the fit is best shown by overlaying transparencies of the model onto the images. The format of publication precludes this, but readers can copy the model onto transparencies and make the comparison themselves. Due to low contrast, some features do not reproduce well in the photographs. Figure 5 therefore provides a drawing of the major dust lanes visible to $\sim 120''$. Features reproduced by the model are drawn with a solid line. Features not explained are dashed.

In the inner region, virtually all major features are reproduced by the model. A notable exception is a linear feature (dotted in Fig. 5) which cannot be explained as a path-length effect through the twisted disk. It is, however, consistent with a circular ring of enhanced dust density within the twisted disk.

The model accurately reproduces smoothly connected dust lanes all the way from the center to $\sim 90''$. Note that the dust lane reproduced by the model on the left (east) side of Fig. 4 is much fainter than its prominent analogue on the right side. Only portions of it are faintly visible in

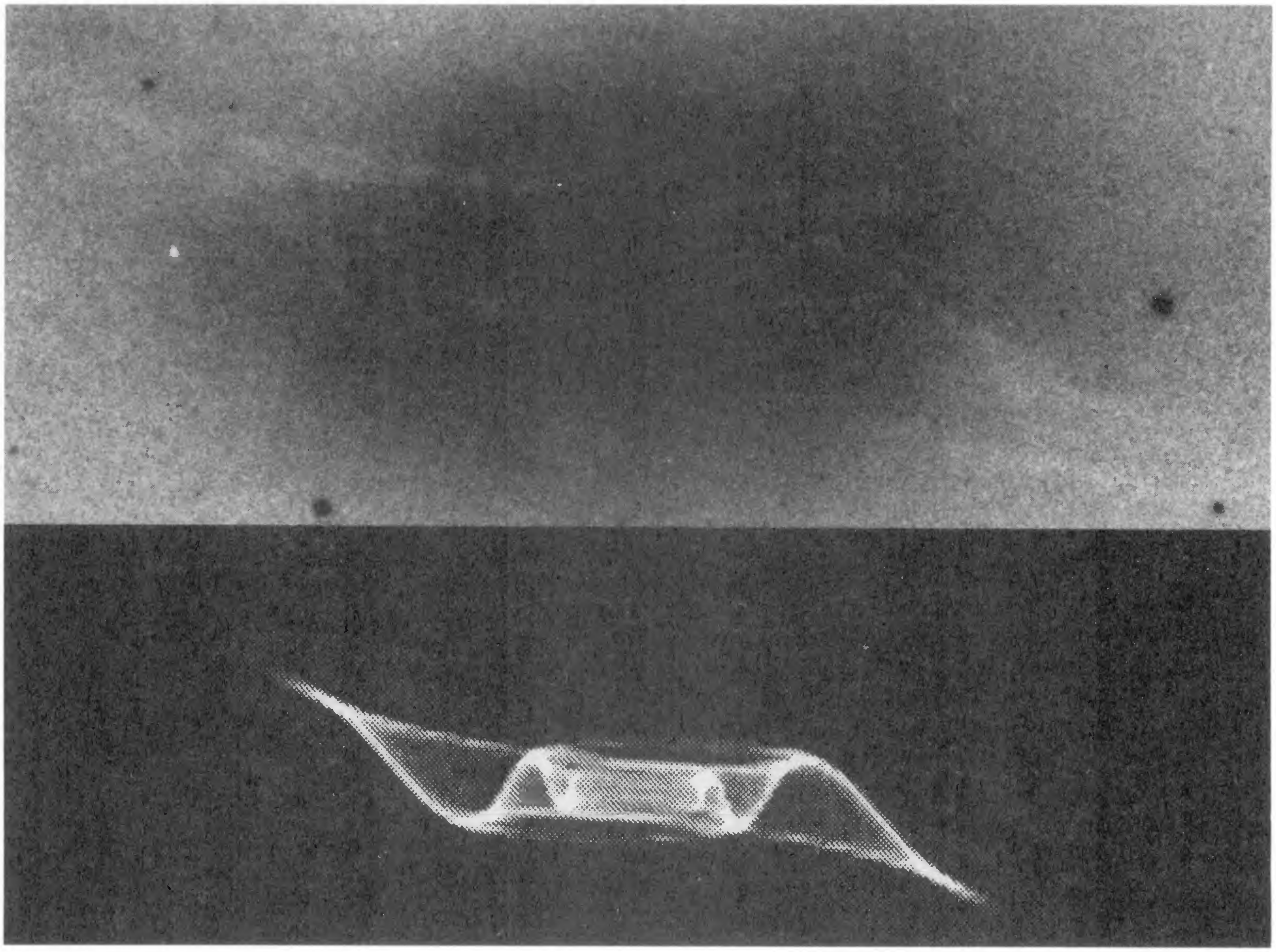

FIG. 4. Model fit to NGC 4753 over the radius range 13″ to 90″. The model accurately reproduces continuous, smoothly connected dust lanes over its entire radial extent. However, note that the dust lane corresponding to the model on the left (eastern) side of the galaxy is very faint and only partially visible in the photograph. The western analogue of this feature is prominent. These features along with several dust lanes not explained by the model are detailed in Fig. 5.

the reproduction (see Fig. 5). Several dust features at larger radii are not explained by the model (dashed in Fig. 5). These are not symmetric about the center, but rather are somewhat concentrated on the eastern side of the galaxy. This could be material at still larger radii. Due to their asymmetry, any disk model will have trouble explaining these features. The inability of our model to fit many of the outer dust lanes argues for some caution in our interpretations. Nonetheless, the fact that the model reproduces smoothly connected, continuous dust lanes from the center to $\sim 90''$ suggests that the three-dimensional geometry of the disk is understood over this radial range and that it provides an accurate probe of the potential over the full radial range of the model.

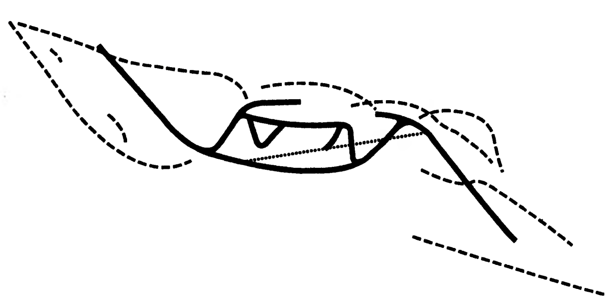

FIG. 5. A line drawing of the major dust lanes in NGC 4753. Features drawn with a solid line are explained by the model as regions where the line-of-sight is nearly tangential to the twisted disk. Features shown with dashed lines are not explained by the model. The nearly linear feature (dotted) is consistent with a circular ring of enhanced dust formation within the twisted disk.

Extension of the disk model to $r > 90''$ reveals little twisting in its outer regions and hence no predicted dust lanes due to line-of-sight effects. In projection, the model disk beyond 90″ appears as an ellipse whose major axis is roughly aligned with the outermost portions of the dust lanes fit by the model. It is interesting to note that luminous extensions of the galaxy beyond $\sim 120''$ appear on both sides of the galaxy at the same position angle as the extended disk model (see for example the Palomar Sky Survey) suggesting either that star formation has occurred in the outer regions of this disk or that a stellar component was accreted along with the gas. While star formation has probably occurred in the inner regions, the luminosity of

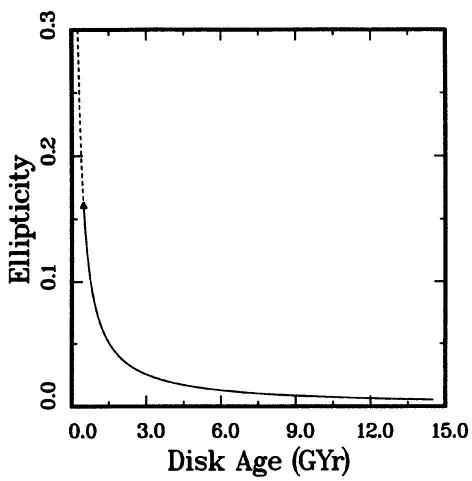

FIG. 6. The relationship between the age of the accretion disk in NGC 4753 and the ellipticity ϵ of the galactic mass distribution. Here the distance to NGC 4753 is assumed to be 8.7 Mpc and $v_c = 300$ km s^{-1}. A lower limit on the ellipticity is provided by a disk age equal to the Hubble time. Physical arguments provided in the text suggest that the disk has an age equal to or greater than 6 orbital periods as measured at 90″ in the disk (shown by triangle in figure). This provides a maximum ellipticity. As discussed in the text, the maximum derived ellipticity is independent of the assumed distance or circular velocity of NGC 4753.

the host galaxy overwhelms any contributions from stars in the twisted disk.

In a twisted disk, self-gravity (Hunter & Toomre 1969; Sparke 1984; Sparke & Casertano 1988) and dissipation (SCD1, SCD2) both lead to warping, i.e., to a change in the inclination as a function of radius. The fact that the twisted disk of NGC 4753 has a constant inclination implies that both self-gravity and dissipational settling have been dynamically unimportant in this disk.

3.3 Geometry of NGC 4753 and the Age of the Disk

With the interpretation of the dust lanes in NGC 4753 as optical depth effects in a twisted disk, the good fit of the model implies that the disk's geometry is well determined. Given this geometry and the assumption that the accreted disk was initially approximately planar requires that $\Omega_p \propto r^{-1}$, to a good approximation, over the radii spanned by our fit. As discussed in Sec. *3.2*, if the galaxy's total mass distribution is approximately spheroidal and if the galaxy has a flat rotation curve, then the isodensity surfaces must all have essentially the same shape. From Eq. (2), from the definition of η, and from the model values of T and i_0, the ellipticity of the *mass* distribution $\epsilon = 1-(c/a)$ is given by

$$(1-\epsilon)^2 = (c/a)^2 = (1-9.1\tau_0/t)/(1+4.6\tau_0/t), \qquad (3)$$

where t is the age of the disk and τ_0 is the orbital period at r_0 (for an assumed distance of 8.7 Mpc, $r_0 = 0.55$ Kpc and $\tau_0 = 1.1\times10^7$ yr). Thus a relationship exists between the age of the twisted disk and the shape of the galactic mass distribution. This relationship is shown in Fig. 6. Note from Eq. (3) that $t < 9.1\tau_0$ is not allowed. This is a manifestation of the "dimpling" described in Sec. *3.2* of isodensity surfaces in the scale-free model. For values of t (or, conversely, c/a) which are relevant to the model for NGC 4753 this dimpling is not significant.

Unfortunately, t and ϵ cannot be determined independently. However, limits can be placed on the age of the disk which, in turn, provide limits on the ellipticity. If the disk is as old as a Hubble age, then the total mass distribution is very nearly spherical, i.e., $\epsilon < 0.01$. On the other hand, arguments concerning the minimum age of the accretion disk lead to an upper limit for the ellipticity. Inspection of the field near NGC 4753 reveals an absence of nearby companions from which material may have been tidally captured. This suggests that the accreted material came from the merger of a gas rich dwarf companion. Simulations of disk formation resulting from such mergers indicate that several orbital periods, at least a half dozen or more, are required for the accreted material to smear out into a disk (Varnas 1986a; Rix & Katz 1991). The twisted disk in NGC 4753 appears fully developed, i.e., well spread over all azimuthal angles to at least $\sim$90″, and perhaps to $\gtrsim$120″ (based on the extended luminosity seen at the position angle of the outer disk). This suggests that the disk has an age equal to or greater than 6 orbital periods as measured at 90″, i.e., $t \geqslant 0.47$ Gyr for the assumed distance of 8.7 Mpc. The chaotic dust lanes beyond $\sim$90″ suggest that the disk age may be somewhere in the range 0.5–1.0 Gyr. While a lesser age for the disk cannot be entirely ruled out, it is difficult to understand how a younger disk could be as fully formed in its outer regions. An age equal to or greater than 6 orbital periods at 90″ implies $\epsilon \leqslant 0.16$. An independent means for dating the accretion disk would provide the exact flattening of the galaxy.

It is important to note that uncertainties in the assumed distance to NGC 4753 and/or the circular velocity do not affect the upper limit on the ellipticity. This is seen by expressing t and τ_0 in Eq. (3) in terms of the orbit periods at r and r_0, i.e., $t = n(2\pi D\theta/v_c)$ and $\tau_0 = (2\pi D\theta_0/v_c)$ where θ is the angular distance from the center of NGC 4753, D is the distance to NGC 4753, and n is the age of the disk, in orbit periods, at r ($=D\theta$). From this, we find that $\tau_0/t = \theta_0/n\theta$. Then the upper limit on ϵ given by Eq. (3) is independent of both the assumed distance to the galaxy and to v_c, provided $v_c = constant$ so that $n \propto 1/\theta$.

As pointed out earlier, the self-gravity of the twisted disk has played a negligible role in its evolution compared with precessional forces arising from the nonsphericity of the galaxy. For a given disk mass, the ellipticity of the galaxy must be greater than a particular value for the disk's self-gravity to be unimportant compared with precessional twisting. Jura (1986) has estimated the mass of the interstellar matter in NGC 4753 to be 1.0 to $1.8\times10^8 \mathscr{M}_\odot$ (corrected for an assumed distance of 8.7 Mpc; Jura assumed a distance of 11.4 Mpc), though no determination of the distribution of this material was possible. A lower limit on ϵ and an upper limit on the age could be determined if both the mass and the density distribution of the captured disk were measured. Observations at 21 cm with higher resolution would be helpful in this regard.

The model described above assumes $\dot{\Omega}_p \propto r^{\alpha}$, with $\alpha = -1$ [see Eq. (2)]. A series of models with the precession rate set by $\dot{\Omega}_p = -(3v_c/4)r^{\alpha}\eta \cos i$, with $\alpha \neq -1$, were used to determine the range of α compatible with observations. For mass distributions which are not highly flattened, this precession law follows from the gravitational potential $\Phi = (v_c^2/2)[\ln r^2 + \eta_0(r/r_0)^{(\alpha+1)}P_2(\cos\theta)]$, where η_0 is determined at r_0 and P_2 is the $l=2$ Legendere polynomial [cf., Eq. (4b) of Steiman-Cameron & Durisen 1988]. The density distribution leading to Φ follows from Poisson's equation, thus allowing axis ratios for isodensity surfaces to be determined. Constant ellipticity with radius corresponds to $\alpha = -1$, while $\alpha < -1.0$ ($\alpha > -1.0$) corresponds with decreasing (increasing) ellipticity with radius. Thus limits on α allow constraints to be placed on the radial *change* in ellipticity.

Comparisons between models and observations reveal reasonable agreement for $-0.89 \leqslant \alpha \leqslant -1.14$ between 17″ and 90″. (Limits on α were not as constrained for $r < 17''$ suggesting, perhaps, that the luminous component is a more important contribution at small radii.) This range of α implies that the ellipticity of the mass distribution is constant to better than 20% over this range. Thus the shape of the galaxy's mass distribution is essentially constant with radius, isodensity surfaces varying no more than twenty percent over a factor of nearly five in radius.

The derivation of the galaxy's shape assumes that the circular velocity is constant. Unfortunately, the observations of Chromey (1973) do not allow us to determine v_c or to check our assumption that v_c=constant (see Sec. *3.2*). If v_c decreases outward, then the ellipticity would have to increase with radius in order to maintain an r^{-1} precession rate. The opposite behavior would be required for a rising rotation curve.

3.4 Precessional Effects of the Luminous Galaxy

While the above demonstrates that a nearly spherical halo can account for the twist observed in the dusty disk of NGC 4753, it is important to inquire whether or not the mass associated with the luminous component of the galaxy is sufficient. This determination requires knowledge of both the underlying light distribution and $\mathscr{M}/L$. Unfortunately, the former is difficult to determine from our observations alone due to intervening dust. Any derived light distribution will be dependent upon the assumed model for the dust distribution in three-dimensions. The observational data are sufficient, however, to show that the core of the true light distribution of NGC 4753 is probably unresolved. This is consistent with the low luminosity of the galaxy. If constant $\mathscr{M}/L$ held, and if the underlying light distribution is typical of elliptical galaxies or the bulges of S0 systems, then the rotation curve should peak at a radius well inside the inner edge of the twisted disk and become near-Keplerian. This seems inconsistent with the observations of Chromey (1973), which suggests that $\mathscr{M}/L$ is not constant with radius.

In any case, to test whether the mass associated with the luminous matter can explain the observed twisted disk, let us assume that $\mathscr{M}/L$ is a smoothly varying function of radius which is constant on isoemmissivity surfaces. In the absence of dark matter, the flattening of the light distribution would then provide a measure of the flattening of the overall mass distribution. If this mass distribution could produce the twist seen in the dusty disk of NGC 4753, there would be no need to invoke a dark-matter halo. To examine this possibility, knowledge of both the flattening of the isodensity (isoemmissivity) surfaces and the radial density profile [i.e., $\mathscr{M}(r)/L(r)$] is required.

Consistent with the results of the analytic model, we will assume that flattening does not change with radius. Relaxation of this assumption does not change our findings. The *Reference Catalogue of Bright Galaxies* provides an axis ratio of 0.45 (de Vaucouleurs & de Vaucouleurs 1964) for NGC 4753. The outline of the unsharp-masked area in Fig. 1 is the shape obtained by the VISTA profile fitter for that isophote, namely 58″×84″ or an axis ratio of 0.69. However, the dust certainly affects this measurement. Because the dust is aligned generally along the apparent major axis, the true shape of this isophote is probably considerably flatter. Planned observations in the infrared will serve to better constrain the flattening of the underlying luminosity.

We still require knowledge of the radial density profile or, equivalently, the circular rotation curve. As before, the assumption of a flat rotation curve is adopted; implications of a rising or falling rotation curve were discussed in Sec. *3.3*. We now have returned essentially to the scale-free model discussed earlier; a model galaxy with similar, concentric (approximately) spheroidal isodensity surfaces and a circular velocity which is constant with radius. Therefore Eq. (3) can be used to determine the age of the twisted disk. For (c/a=0.69 (0.45) this expression gives an age for the disk equivalent to 3.1 (1.8) orbit periods at 90″ if the luminous matter alone is responsible for the precessional torques. As before, it is difficult to understand how the disk could be fully formed in such a short time. This difficulty is compounded by the apparent extension of a stellar disk to at least 120″. The age of the disk would be only 2.3 (1.4) orbit periods at this radius.

Additional observations of NGC 4753 which constrain the circular rotation curve and underlying light distribution are clearly required to clarify the assumptions above. Nonetheless, unless one of our assumptions concerning the characteristics of the luminous component of NGC 4753 is seriously deficient, or unless a well formed disk can develop from a merger on a time scale characteristic of an orbital period, a situation we consider unlikely, then for any reasonable estimate of the disk's age, the distribution of luminous matter in NGC 4753 is flatter, possibly by a substantial amount, than the total mass distribution. Thus an r^{-1} dependence of the precession rate indicates that a massive, nearly spherical halo dominates the gravitational potential of the galaxy over most of the radial range of our fit.

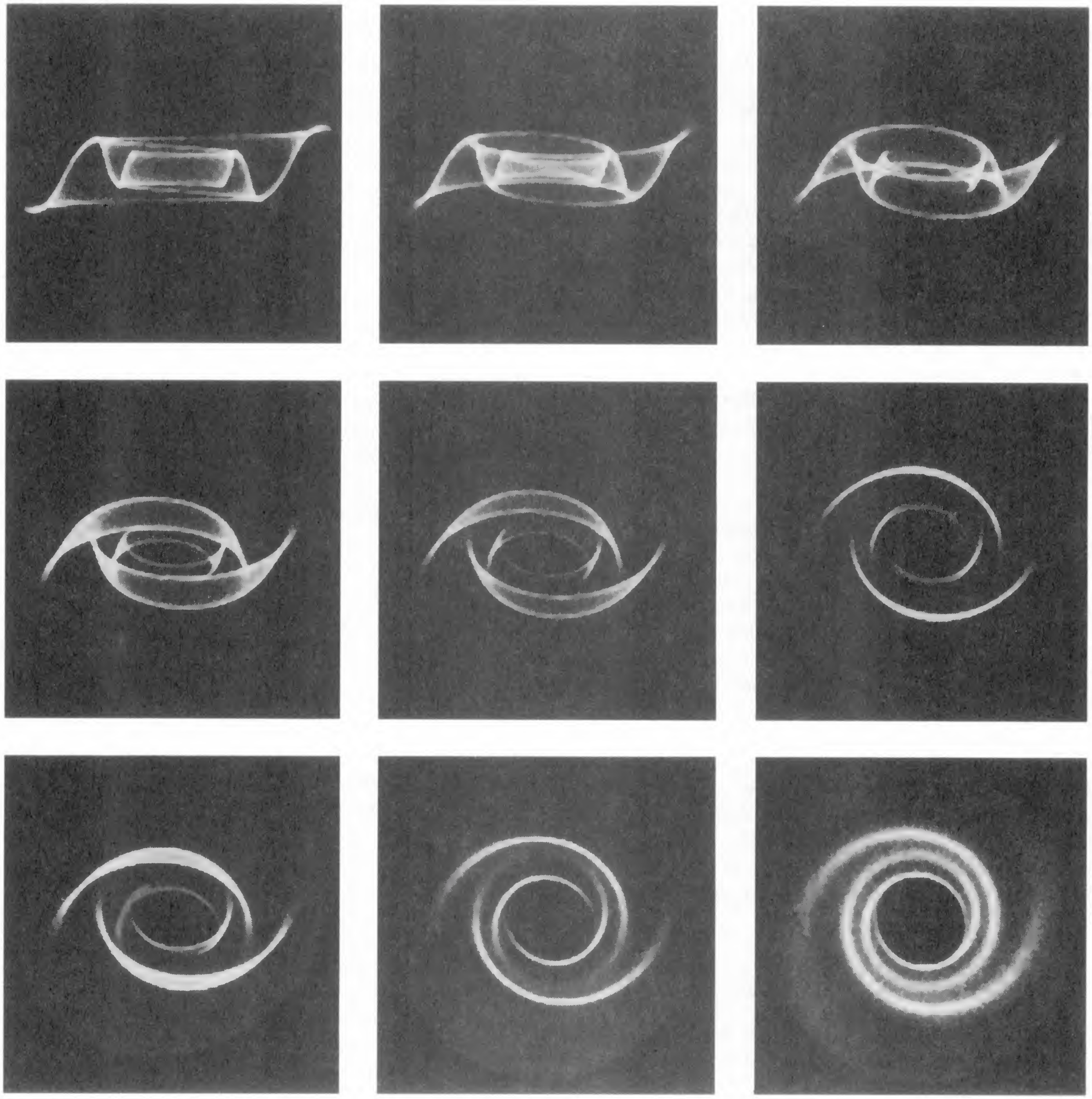

FIG. 7. The appearance of the model as seen from various directions. From left to right and then top to bottom, the inclination of the line of sight to the equatorial plane of the galaxy ranges from 0° to 90° in steps of 10°. As discussed in the text, although systems similar to NGC 4753 may not be rare, only certain viewing orientations are conducive to easy identification of a highly twisted disk.

3.5 Viscosity

Inherent in $\aleph$ is information about the effective viscosity of the disk. Initially we hoped that model fits would allow the determination of $\aleph$ and hence provide fundamental information on dissipation in captured disks. However, because the disk inclination has remained nearly constant while the disk has twisted by nearly 4π radians, only an upper limit can be placed on $\aleph$ and hence on the viscosity of the disk.

Based on the assumption that cloud–cloud interactions are the dominant source of dissipation for settling in galactic disks, SCD1 developed a simple analytic estimate for the maximum permissable value of the coefficient of kinematic viscosity $\nu_{\max}$. This is given by Eq. (10) of SCD2 for the scale-free model used here. It in turn provides a maximum value of $\aleph$ via Eq. (12a) of SCD2. The model-determined value of $\aleph$ for NGC 4753 implies that ν is $\sim$0.2%–4% of $\nu_{\max}$ for an assumed cloud velocity dispersion of 10 km s^{-1}. The smaller ratios of $\nu/\nu_{\max}$ correspond to the smaller ellipticities in Fig. 6. The calculation of $\nu_{\max}$ assumes that the mean time between cloud–cloud collisions is equal to one quarter of the epicyclic period. Then

$\nu/\nu_{max} \ll 1$ implies that the mean time between collisions is much shorter or longer than this. Collision times much longer than the epicyclic period are consistent with the low apparent mass of the captured disk that is implied by the unimportance of self-gravity and by its low optical depth. We cannot rule out other explanations for the small value of ν. For example, the cloud velocity dispersion could be less than 10 km s^{-1} ($\nu_{max} \propto v_{rms}^2$), or cloud–cloud collisions may not be the dominant source of viscosity, or individual cloud–cloud interactions may be less efficient in transporting angular momentum than suggested by the simple arguments of SCD1.

Quillen *et al.* (1992) have found that a twisted disk model similar to the one presented here is required to fit kinematic observations of molecular gas in NGC 5128 (Cen A). The twisted disk in Cen A also appears to be unsettled. Quillen *et al.* argue that this is consistent with age constraints if a viscosity law proportional to the normal optical depth of the disk is used (Goldreich & Tremaine 1978).

3.6 Visual Appearance of Twisted Disks

The type of accretion event responsible for the appearance of NGC 4753 could be fairly common. The fact that we are able to recognize it in NGC 4753 is due, in part, to the fortuitous viewing orientation and the low capture inclination. It is also due to favorable optical depth conditions in the gas disk so that dust lanes due to caustics are readily visible through intervening sheets of the disk. The appearance of a twisted disk is a strong function of viewing orientation. This is illustrated in Fig. 7, where our model of the disk is shown from various viewing orientations. At low inclination, where line-of-sight path lengths through the disk are similar to that of NGC 4753, we see the curved caustics characteristic of the large twist in the disk. At viewing orientations close to the equatorial plane of a highly flattened host galaxy, much of the twisted disk will not lie in front of, and thus obscure, luminous regions. Thus nearly edge-on twisted disks may be difficult to identify. Conversely, if the twisted disk is viewed nearly face-on, then the galaxy may be misidentified as a barred or grand-design spiral. Since approximately half of all viewing orientations produce spiral or bar-like features, we wonder whether some galaxies which have experienced accretion events have been misclassified as "normal" spirals.

4. SUMMARY

We show that the appearance of the prominent and complex dust lanes in the peculiar S0 galaxy NGC 4753 can be explained as optical depth effects in a strongly twisted disk. The structure of this disk has been used to investigate the galaxy's three-dimensional distribution of matter. Our models imply that the disk is the product of an accretion event and was formed at an inclination of $\sim 15°$ with respect to the equatorial plane of the accreting galaxy. The shape of the galaxy's total mass distribution is oblate if the sense of rotation of the twisted disk is the same as the stellar disk. Since the accretion event, differential precession has caused the disk to be twisted by 3.8π over a factor of seven in radius. This twist leads to large path-lengths through the disk along certain lines-of-sight. Excellent agreement is found between the increased path-lengths in the model and the observed dust lanes in NGC 4753. This interpretation of the dust lanes indicates that most of the galaxy's mass is nearly spherically distributed and that the isodensity surfaces of this distribution have the same flattening, ellipticity constant to within 20%, over the radial range 17″ to 90″ (=0.7 to 4 kpc at a distance of 8.7 Mpc). The flattening of the total mass distribution and the age of the accretion disk cannot be determined independently. However, physical arguments constrain this distribution to be no flatter than E1.6 and no "rounder" than E0.1. These limits are rounder than the luminous matter and so would seem to require the presence of dark matter. The lack of appreciable settling towards the equatorial plane places an upper limit on the effective coefficient of kinematic viscosity for the disk which is less than a few percent of the maximum permissable value as given by Steiman-Cameron & Durisen (1990).

We have given only a brief discussion of the temporal development of the accreted disk. However, we have produced a video that shows the evolution in detail. It also illustrates the three-dimensional geometry of the present disk much better than any projection can. A copy of the video can be obtained by sending a blank VHS-format tape to the lead author of this paper.

The authors would like to thank A. Sandage for providing the photo shown in Figs. 2 and 4 and J. Stauffer for connecting the authors in this work. In addition, we would like to thank our anonymous referee for suggestions and comments which have improved this paper. T.S.-C. would like to thank B. Smith for discussions and support. This research was supported in part by National Science Foundation Grant Nos. AST-8520142 and AST-8915021. One of us (R.H.D.) enjoyed the hospitality of Max Planck Institut für Extraterrestrische Physik and the support of a Fulbright Partial Maintenance Award during completion of this manuscript.

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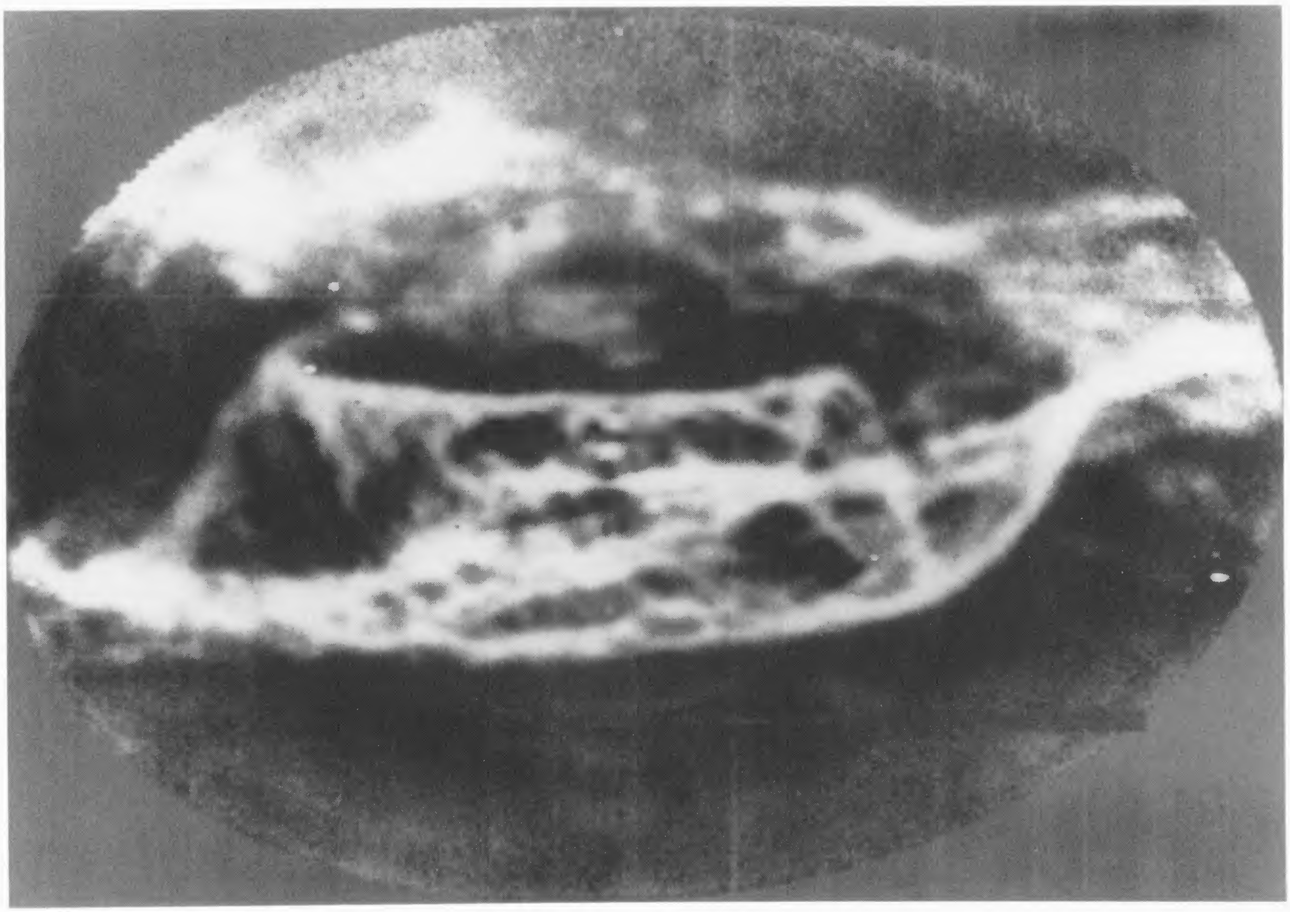

FIG. 1. A *V*-band CCD image of the inner regions of NGC 4753. The smoothed radial brightness profile has been divided out so that the complex dust features can be illustrated as a function of radius. North is towards the top and west to the left (see Fig. 2). The dimensions of the oval area are 84″×58″.

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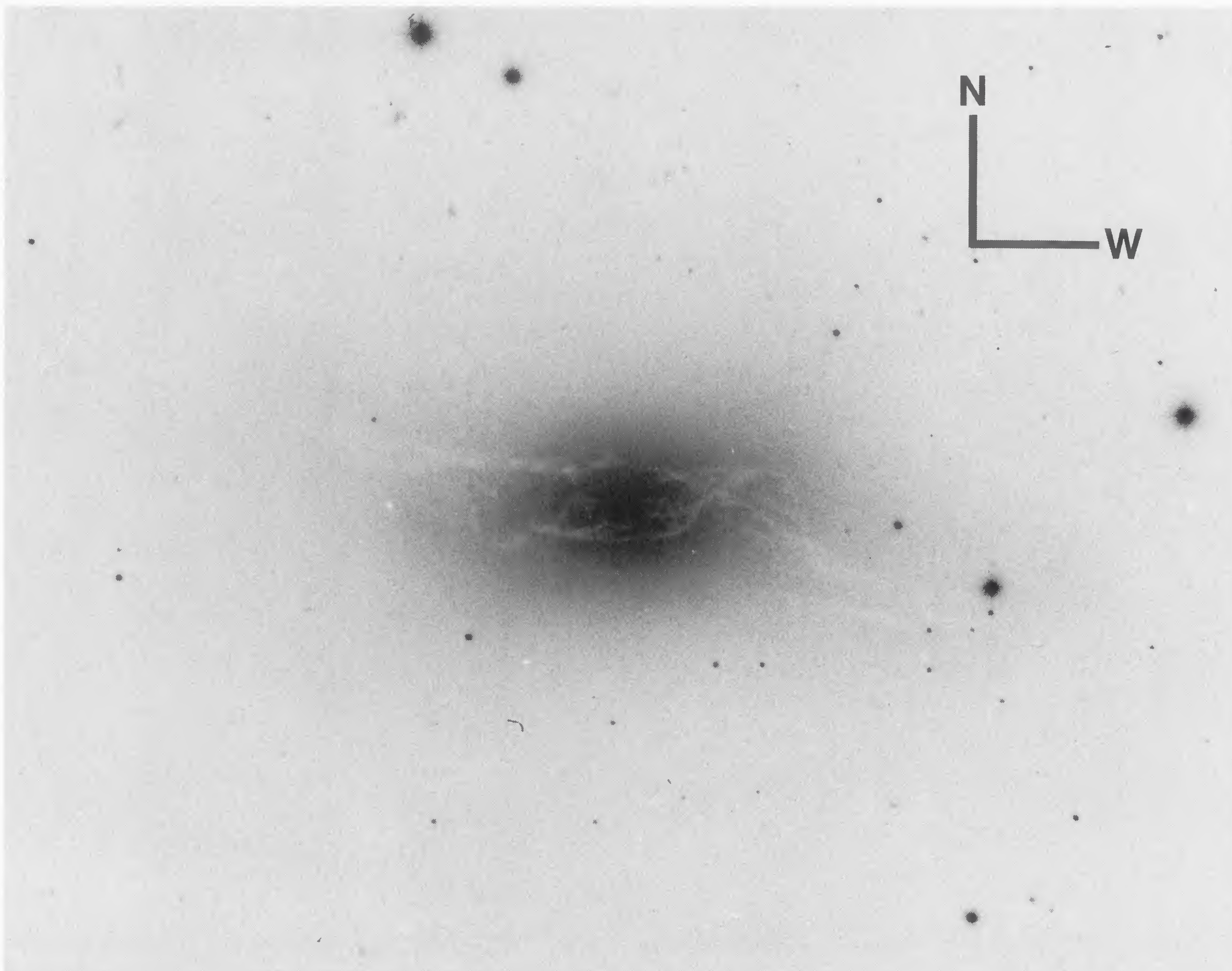

FIG. 2. The dust lanes of NGC 4753 out to a radius of ~130″ (photo courtesy A. Sandage).

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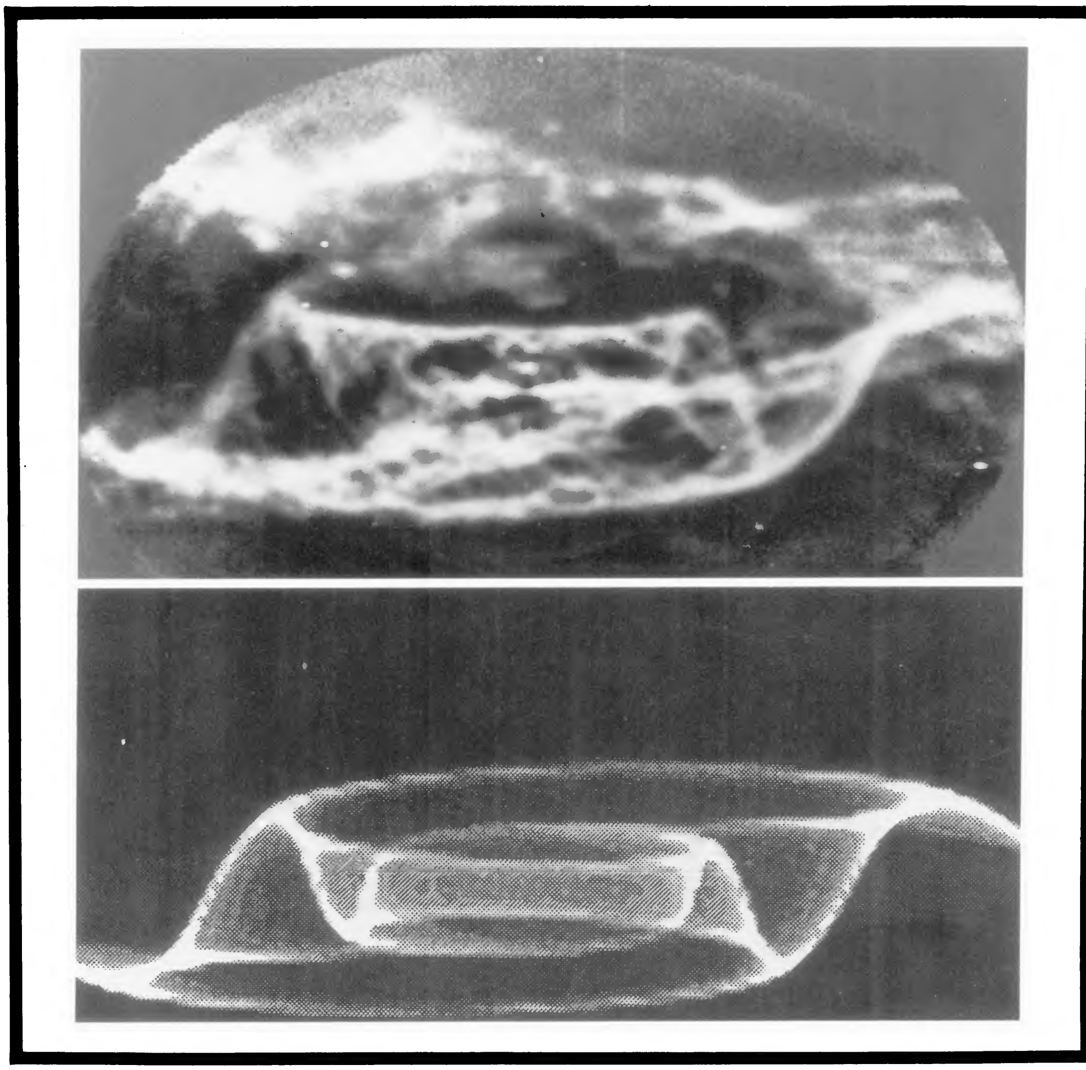

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