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NUCLEAR STELLAR DISKS IN SPIRAL GALAXIES[1]

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ABSTRACT

We report evidence for nuclear stellar disks in three early-type spirals, namely, NGC 1425, NGC 3898, and NGC 4698, revealed by Wide Field Planetary Camera 2 F606W images out of a sample of 38 spiral galaxies, selected from the *Hubble Space Telescope* data archive. Adopting the photometric method introduced by Scorza & Bender, we derived their central surface brightness and scale length by assuming them to be infinitesimally thin exponential disks. No nuclear disk was found in barred galaxies or galaxies of Hubble type later than Sb. The external origin of the disk in NGC 4698 is strongly suggested by its orthogonal geometrical decoupling with respect to the host galaxy.

Subject headings: galaxies: individual (NGC 1425, NGC 3898, NGC 4698) — galaxies: photometry — galaxies: spiral — galaxies: structure

1. INTRODUCTION

In the last decade, embedded stellar disks or disky distortions have been found in many elliptical and S0 galaxies (Scorza & Bender 1995, hereafter SB95; Seifert & Scorza 1996). They are characterized by a smaller scale length and higher central surface brightness with respect to the large kiloparsec scale disks typical of lenticular and spiral galaxies. The existence of embedded disks gives further observational support to the idea that the disky ellipticals are the continuation of the sequence ranging from Im through spiral to S0 galaxies (Kormendy & Bender 1996 and references therein). This suggests also a continuity in the formation history, whereby one or several parameters of the protogalaxy vary smoothly (e.g., van den Bosch 1998).

Subarcsecond resolution provided by state-of-the-art ground- and space-based telescopes have revealed even smaller stellar disks in the nuclear region of nearby galaxies. To date, the smallest disks we know have scale lengths of few tens of parsecs, and they have been identified in the nucleus of a handful of early-type disk galaxies: the S0 galaxies NGC 3115 (SB95; Lauer et al. 1995), NGC 4342 (van den Bosch, Jaffe, & van der Marel 1998; Scorza & van den Bosch 1998), and S0 NGC 4570 (van den Bosch et al. 1998; Scorza & van den Bosch 1998; van den Bosch & Emsellem 1998), and the Sa NGC 4594 (Burkhead 1986, 1991; Kormendy 1988; Emsellem et al. 1994, 1996). In addition, nuclear stellar disks of gas, dust, and stars have been found in the E3 galaxy NGC 5845 (Kormendy et al. 1994) and in the dwarf E2 galaxy NGC 4486A (Kormendy et al. 2002). Although the photometric parameters are not known, these stellar disks appear to be similar to those of NGC 3115 and NGC 4594. This phenomenon may be more common if some of the E and S0 galaxies with disky isophotes observed by Ravindranath et al. (2001) and Rest et al. (2001) turn out to host a nuclear stellar disk.

The presence of nuclear disks raises the question about the epoch (i.e., coeval or not with that of the host) and mechanism (i.e., external or internal origin) of their formation. Indeed, it is possible that they formed with a different mechanism than the one that formed normal S0 disks, since their size is 1 order of magnitude smaller. The blue color of the nuclear disks of NGC 4342, NGC 4570, and NGC 4486A suggests they are made of younger stars with respect to the bulk of their host galaxy (van den Bosch et al. 1998; Kormendy et al. 2002). In the framework of galaxy formation via hierarchical merging, acquired gas may end up forming some of these nuclear stellar disks. On the other hand, they could be built up from gas transported toward the galaxy center during the secular evolution of a bar. This seems to be the case of NGC 4570 (van den Bosch & Emsellem 1998), in which the observed features in photometry and kinematics correspond with the position of the main resonances of a small bar. Furthermore, any model for the formation of nuclear disks has to account for supermassive black holes, which are supposed to reside in every galaxy and whose gravitational influence may extend to parsec scales of the disks. Galaxies hosting nuclear disks are not exceptions in this context, as NGC 3115, NGC 4342, NGC 4594, and NGC 5845 are known to harbor a central supermassive black hole (Kormendy et al. 1996a, 1996b; Cretton & van den Bosch 1999; Kormendy & Gebhardt 2002).

To date, studies on nuclear stellar disks considered mainly elliptical or S0 galaxies, but there is no a priori reason why they should not also be present in spiral galaxies. Would this be true, such nuclear disks would be the result of star formation by gas either driven toward the center by a bar instability or acquired from the outside.

For these reasons, we undertook a search for nuclear stellar disks in spiral galaxies based on *HST* Wide Field Planetary Camera 2 (WFPC2) archive images. In this paper we present as a result of our investigation three new cases of spiral galaxies hosting a nuclear disk embedded in their main outer disk and bulge.

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2. SEARCHING FOR NUCLEAR STELLAR DISKS IN SPIRALS

2.1. *Sample Selection*

We selected RC3 (de Vaucouleurs et al. 1991) galaxies classified as spiral ($T \geq 0$) and with $cz < 2000$ km s^{-1}. We restricted our sample to galaxies within 20 Mpc (for $H_0 = 100$ km s^{-1} Mpc^{-1}) to be able to detect 10 pc scale length nuclear disks on WFPC2/PC frames out to about 2–3 scale lengths. We did not exclude low-inclined galaxies from the sample, since nuclear disks might have a different inclination with respect to their hosts. We searched the *HST* science archive looking for all the available images. We realized that WFPC2 F606W was the only camera/filter combination producing a homogeneous sample large enough for our purposes (159 galaxies). This resulted in a sample of 112

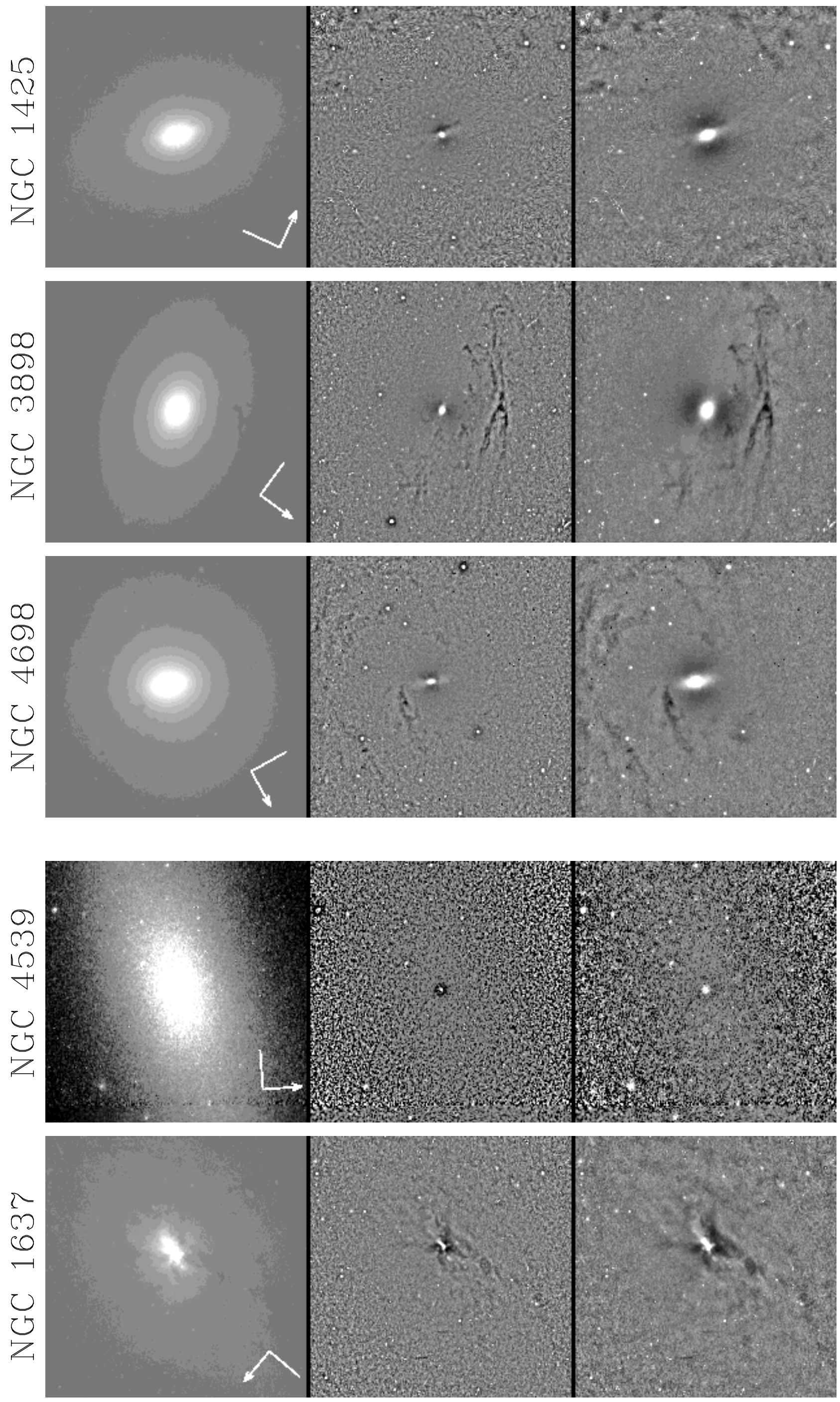

FIG. 1.—*Left:* WFPC2 F606W images of NGC 1425, NGC 3898, and NGC 4698 (where we found a nuclear disk), NGC 4539 (where a nuclear disk is not present), and NGC 1637 (where dust patches prevent any further analysis). The size of the plotted region is 19$''$.3 × 19$''$.3. The orientation is specified by the arrow indicating north and the segment indicating east in the bottom right corner of each panel. *Middle and right:* Unsharp masking of the WFPC2 F606W images obtained with $\sigma = 2$ and 6 pixels, respectively. Sizes and orientations are the same as in the left panels.

objects after we rejected those frames in which the galaxy nucleus was out or too close to the chip edge, as well as those with too-short exposure times.

It has to be noted that all but three of the selected galaxies belong to four *Supernova/Acceleration Probe* (SNAPSHOT) observing programs: (1) 57 objects were taken from the sample of disk galaxies ranging from E/S0 to spiral galaxies observed in Program ID 5446 (PI: G. Illingworth); (2) 33 are unbarred Sa/Sb spiral galaxies from Program ID 6359 (PI: M. Stiavelli); (3) 14 spirals were taken from the nearby Seyfert galaxies observed in Program ID 5479 (PI: M. Malkan); (4) five are Seyfert spiral galaxies from Program ID 8597 (PI: M. Regan). In our final sample, the Hubble types ranging from Sa to Scd are well represented, and the number of barred spirals roughly equals that of unbarred ones, although images were collected from *HST* programs based on different selection criteria.

2.2. *Analysis of the HST Archive Images*

The on-the-fly calibrated WFPC2 F606W images of the 112 sample galaxies were retrieved from the *HST* archive. The different images of the same target were aligned and combined. Cosmic-ray events were removed with IRAF tasks CRREJ and IMEDIT. The conversion to the Johnson system has been calculated using SYNPHOT in STSDAS. Since this correction depends on the spectral energy distribution of the object, it has been calculated using the Kinney et al. (1996) spectral templates.

As a first step in identifying candidates hosting a nuclear disk, we construct unsharp-masked images for all the sample galaxies, dividing each WFPC2 F606W frame by itself after being convolved with a circular Gaussian of $\sigma = 2$, 4, and 6 pixels, respectively (Fig. 1). The advantage of this procedure is that it quickly enhances any surface brightness fluctuation and noncircular structure extending over a spatial region comparable to the σ of the smoothing Gaussian.

In the present context, this first enables us to set apart 74 galaxies whose nucleus is strongly affected by dusts, preventing any further analysis. This is the case of NGC 1637, shown as an example in Figure 1. It should be noted that, in principle, one can check for the presence of dust lanes using images with different filters that are not available for the whole galaxy sample. However, adopting different values for σ in the unsharp mask allows us to clearly reveal dust lanes, when present.

Successively, on the unsharp-masked images of the 38 remaining galaxies, we looked for the highly flattened nuclear structures, which are possibly inclined nuclear disks. Such flattened structures are not artifacts of the unsharp-masking procedure, since they are always associated to a central increase of ellipticity as measured by performing the isophotal analysis using the IRAF task ELLIPSE. This subset of 38 galaxies ranges from Sa to Sm and from $M^0_{B_T} = -15.6$ to -20.0, as shown in Figure 2, and represents our qualified sample for which we are confident we are able to detect an inclined nuclear disk, if present. We found three objects, namely, NGC 1425, NGC 3898, and NGC 4698, which show this flattened nuclear structure (Fig. 1). A positive fourth cosine Fourier coefficient (describing the disky deviation of the isophotes from pure ellipses) confirms the presence of a nuclear stellar disk in inner regions of these early-type spirals (Fig. 3). In Figure 1 we show the case of NGC 4539 as an example of those galaxies in which we did not identify any nuclear flattened structure.

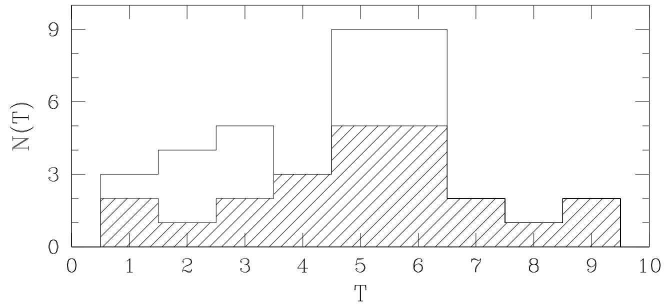

Fig. 2.—Hubble type distribution for the qualified sample of 38 spiral galaxies. The dashed region identifies galaxies with an SB or SAB classification.

2.3. *Photometric Decomposition*

Once the existence of the nuclear disks is established, we derived their photometrical properties by using the method described by SB95. When adopting this technique to study the innermost regions of galaxies, it is essential to restore the images from the effects of the *HST* point-spread function (PSF) in order to properly derive the nuclear disks parameters, as shown by Scorza & van den Bosch (1998). Such deconvolution was performed through the Richardson-Lucy method by means of the IRAF task LUCY. Although susceptible to noise amplification, this algorithm has been proved by van den Bosch et al. (1998) to lead to a restored surface brightness distribution comparable to the one obtained by means of a multi-Gaussian representation (Monnet, Bacon, & Emsellem 1992). We decided to deconvolve the images with a number of iterations between 3 and 6. A larger number of iterations does not affect the result of the decomposition but amplifies the noise. We believe that the results obtained by van den Bosch et al. (1998) are directly applicable to our case; we are dealing with images obtained with similar or longer integration times, galaxies with less-steep surface brightness profiles and nuclear disks with equal or larger scale lengths.

For each given image and nucleus position on the PC (NGC 3898, NGC 4698) or WF2 CCD (NGC 1425), we adopted a model PSF calculated using the Tiny Tim package (Krist & Hook 1999). No correction for telescope jitter was necessary. The SB95 method consists of the iterative subtraction from the galaxy image of a thin-disk model. The parameters of such a disk are varied until the departures from perfect ellipses are smallest (i.e., a_4 and a_6 are nearly zero). For the disk component, we assumed an exponential surface brightness profile with central surface brightness μ_0, radial scale length h, and an inclination given by $i = \arccos(b/a)$. We verified that the parameters of nuclear disks resulting from the photometric decomposition are not affected by small changes in PSF (e.g., its generation in different chip positions).

3. RESULTS

The results of the photometric decomposition of the surface brightness distribution of NGC 1425, NGC 3898, and NGC 4698 are shown in Figures 3 and 4. In Figure 3 we plot the ellipticity, position angle, a_4, and a_6 Fourier coefficient

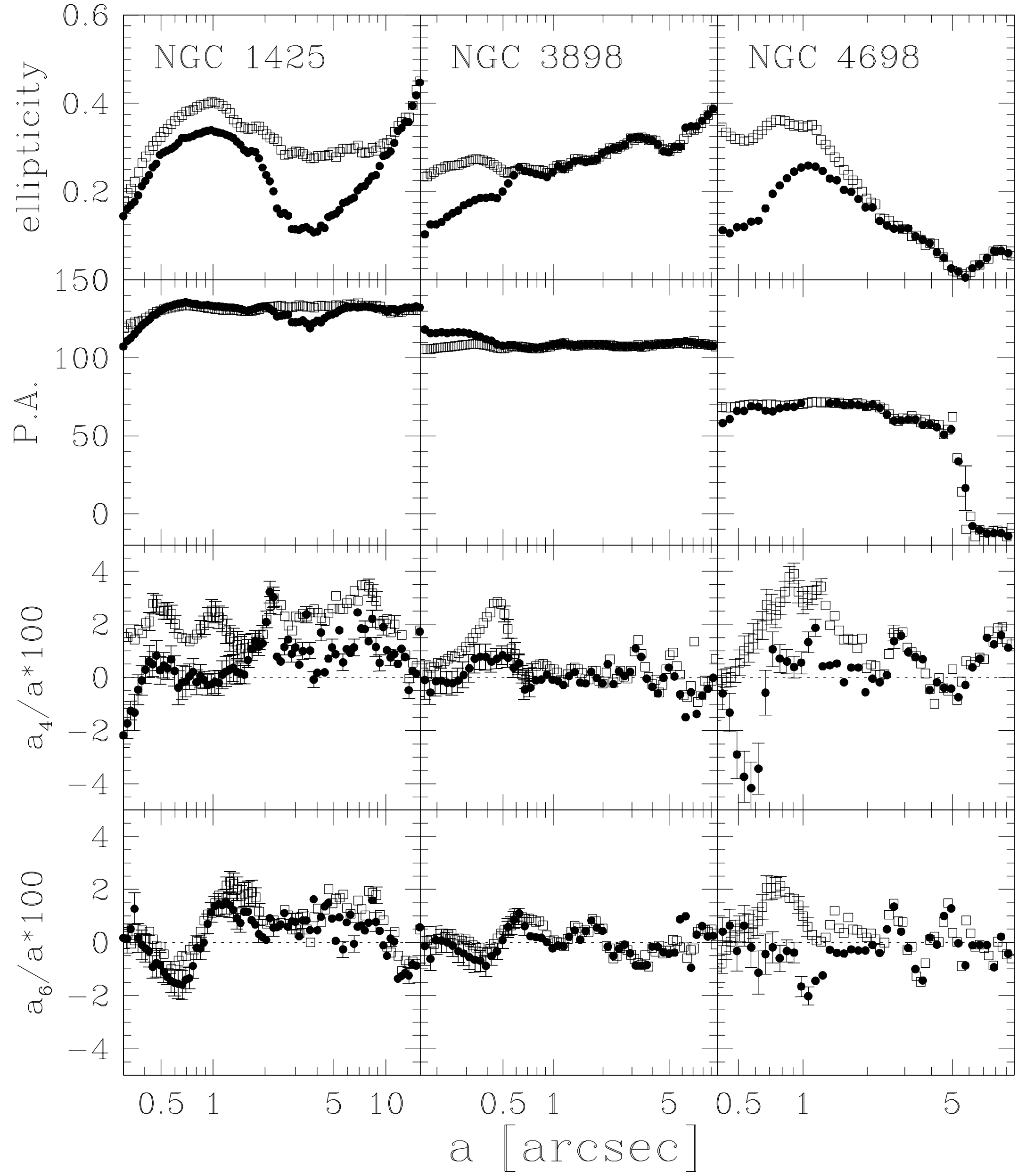

FIG. 3.—Deconvolved radial profiles of ϵ, P.A., a_4, and a_6 Fourier coefficients measured before (*open squares*) and after (*filled circles*) the subtraction of nuclear disks of Table 1 for NGC 1425 (*left panels*), NGC 3898 (*middle panels*), and NGC 4698 (*right panels*). Error bars smaller than symbols are not plotted.

TABLE 1

PARAMETERS OF THE NUCLEAR DISKS AND HOST GALAXIES

	Host Galaxy						Nuclear Disk			
NGC	RC3 Type	RSA Type	D (Mpc)	$M^0_{B_T}$ (mag)	i_{gal} (deg)	P.A.$_{gal}$ (deg)	μ_0 (mag arcsec^{-2})	h (pc)	i (deg)	P.A. (deg)
1425	Sb(s)	Sb(r)	13.1	−19.29	63	129	16.90	26	70	137
							18.53	162	66	135
3898	Sab(s)	Sa	16.4	−19.48	54	107	15.36	18	73	102
4698	Sab(s)	Sa	12.6	−19.04	52	170	17.27	32	74	71

NOTE—Distances are from Tully (1988) with $H_0 = 100$ km s^{-1} Mpc^{-1}. Absolute magnitudes, position angles, and inclinations of the host galaxies are derived from RC3 Morphological types are from RC3 and RSA (Sandage & Tammann 1981).

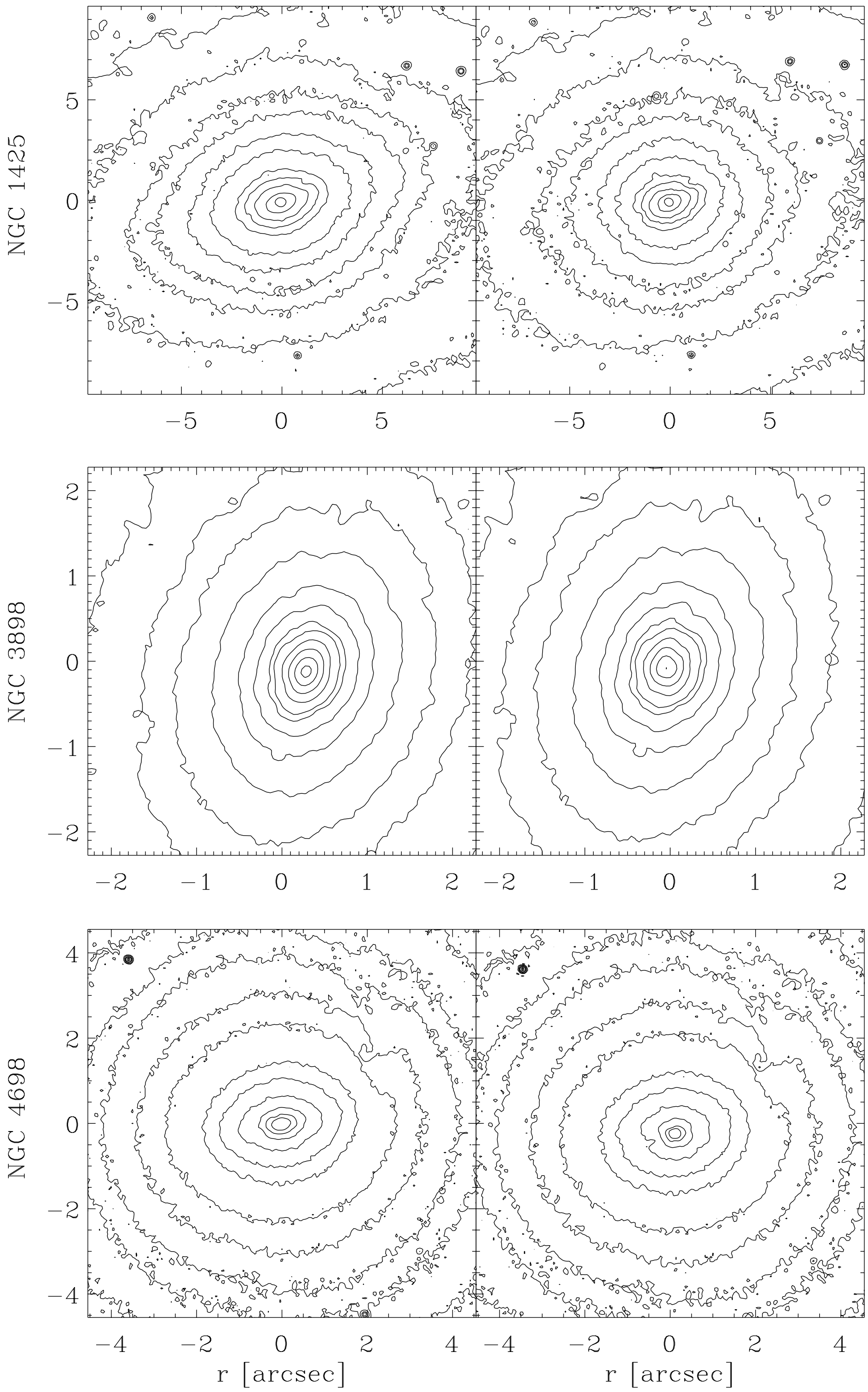

FIG. 4.—Contour plots of the WFPC2 F606W deconvolved images of NGC 1425, NGC 3898, and NGC 4698 before (*left panel*) and after (*right panel*) the nuclear disk subtraction. Scales are in arcseconds, and orientations are the same as in Fig. 1.

radial profiles before and after the nuclear disk subtraction. In Figure 4 the same is true for the galaxy isophotes. The photometric parameters derived for the nuclear disks are given in Table 1. Here we discuss the individual objects:

NGC 1425.—To obtain a residual bulge with nearly elliptical isophotes, we needed to subtract two exponential thin disks of different scale lengths, central surface brightnesses, and inclinations. If this difference in inclination is real, then we are facing two structures in an unstable configuration.

As discussed by Scorza & van den Bosch (1998) for the nuclear and main disks of NGC 4342, it is more likely we are looking at two thick disks of different thicknesses (e.g., the exponential spheroid disks of van den Bosch & de Zeeuw 1996) rather than two infinitesimally thin disks of

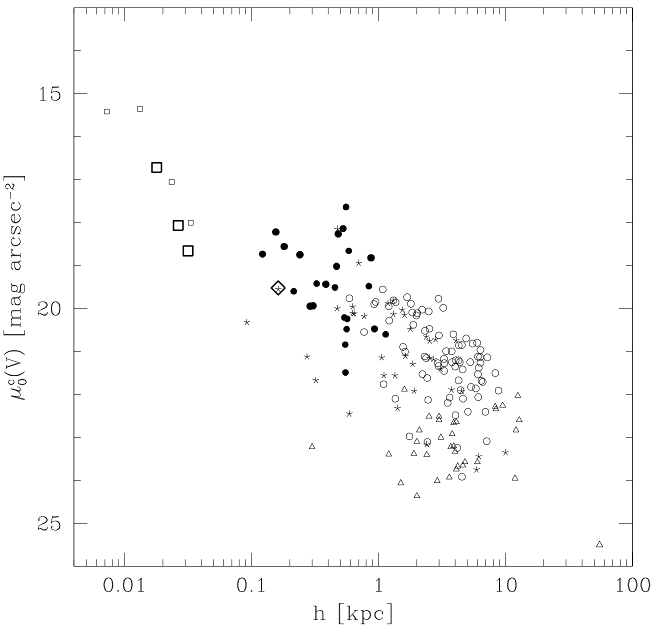

FIG. 5.—Represents μ_0^c-h diagram adapted from van den Bosch (1998). *Open circles*: HSB spirals; *triangles*: LSB spirals; *stars*: S0 galaxies; *filled circles*: disky ellipticals; and *small squares*: nuclear disks in NGC 3115, NGC 4342, NGC 4570, and NGC 4594. Large squares correspond to the nuclear disks found in this paper, while the large diamond indicates the second largest disk found in NGC 1425 (see Table 1 and § 3). The central inclination-corrected surface brightness of nuclear disks is $\mu_0^c = \mu_0 - 2.5\log(\cos i)$.

different inclination. Such a different thickness may be interpreted as indicative of the presence of two distinct exponential disks. Alternatively, we may think we are facing a nonexponential disk with thickness varying with radius. Considering the two-disk hypothesis, we note that the photometric properties of the larger scale disk are close to those observed for disky ellipticals (Fig. 5).

NGC 3898.—The galaxy hosts a small (h = 18 pc) nuclear disk that is noticeable in particular from the Fourier a_4 coefficient positive values, observed within 0″.6. In terms of physical size, this is the smallest disk so far detected. It possibly corresponds to the somewhat steeper rise of the stellar rotation curve measured in the inner 1″ and the two relative maxima in the stellar velocity dispersion at $\pm 1''$ by Vega Beltrán et al. (2001) but not considered in the dynamical modeling of Pignatelli et al. (2001).

NGC 4698.—Although Sandage & Bedke (1994) include this galaxy in The Carnegie Atlas of Galaxies as an example of the early-to-intermediate Sa type, NGC 4698 has photometric and kinematic properties that are uncommon among spiral galaxies. It shows a clear geometrical decoupling between bulge and disk and hosts a kinematically isolated core (Bertola et al. 1999). The nuclear stellar disk corresponds to this isolated core, which is rotating perpendicularly with respect to the galaxy main disk (Bertola et al. 1999).

4. DISCUSSION AND CONCLUSIONS

We have provided evidence for the presence of a nuclear disk in three early-type spirals, namely, NGC 1425, NGC 3898, and NGC 4698, over a qualified sample of 38 objects. The photometric properties of these 20 pc scale exponential disks are consistent with those of the four nuclear disks so far detected in disk galaxies of even earlier morphological type (Fig. 5). We have found nuclear disks neither in Sbc–Sm nor in barred galaxies, although these classes represent the majority of our sample. To further address the demography of nuclear disks, we need to apply the relatively easy approach adopted here (based on unsharp-masking) on a larger sample of galaxies imaged at high spatial resolution in near-infrared passbands to deal with central dusts that prevented us to exclude the presence of nuclear disks in a large fraction (roughly two-thirds) of our WFPC2 F606W sample galaxies.

Without drawing general conclusions from such a limited number of galaxies, nevertheless we have the indication that the presence of nuclear disks is restricted to S0 galaxies and bulge-dominated unbarred spiral galaxies. In the framework of massive bulge formation through a process of hierarchical clustering merging, the nuclear disks may be the final result of dissipational and star formation processes subsequent to a second acquisition event. To date, however, there were only photometric and kinematic evidences that nuclear disks can also be formed via secular evolution of a bar (e.g., NGC 4570).

With NGC 4698 we showed for the first time that second events indeed represent a viable mechanism to build a nuclear disk in the center of disk galaxies. Indeed, the nuclear disk of NGC 4698 is geometrically (this paper) and kinematically (Bertola et al. 1999) decoupled in an orthogonal way with respect to the host galaxy. This phenomenon can hardly be explained without invoking the acquisition of external material from the galaxy outskirts (see Bertola & Corsini 2000).

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