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ANTI-TRUNCATION OF DISKS IN EARLY-TYPE BARRED GALAXIES

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ABSTRACT

The disks of spiral galaxies are commonly thought to be truncated: the radial surface brightness profile steepens sharply beyond a certain radius (3–5 inner-disk scale lengths). Here we present the radial brightness profiles of a number of barred S0–Sb galaxies with the opposite behavior: their outer profiles are distinctly shallower in slope than the main disk profile. We term these “anti-truncations”; they are found in at least 25% of a larger sample of barred S0–Sb galaxies. There are two distinct types of anti-truncations. About one-third show a fairly gradual transition and outer isophotes which are progressively rounder than the main disk isophotes, suggestive of a disk embedded within a more spheroidal outer zone — either the outer extent of the bulge or a separate stellar halo. But the majority of the profiles have rather sharp surface-brightness transitions to the shallower, outer exponential profile and, crucially, outer isophotes which are not significantly rounder than the main disk; in the Sab–Sb galaxies, the outer isophotes include visible spiral arms. This suggests that the outer light is still part of the disk. A subset of these profiles are in galaxies with asymmetric outer isophotes (lopsided or one-armed spirals), suggesting that interactions may be responsible for at least some of the disklike anti-truncations.

Subject headings: galaxies: structure — galaxies: elliptical and lenticular, cD — galaxies: spiral

1. INTRODUCTION

Truncations in the stellar population at the edges of disk galaxies are thought to be a common morphological feature (for a recent review, see Pohlen et al. 2004b). Van der Kruit (1979) and van der Kruit & Searle (1981a,b), using photographic images of mostly late-type, edge-on spirals, found that the exponential decline in surface brightness in the inner disks seemed to change quite abruptly to a steeper decline at the edges of the galaxies. In principle, the faint surface brightness of the outer disk region (face-on $\mu_B \gtrsim 25$) makes truncations easier to detect in edge-on disks, where line-of-sight integration increases the observed surface brightness. However, their very edge-on nature makes it difficult to determine if detected truncations are truly *radial* in nature, as opposed to azimuthal variations due to, e.g., strong spiral arms. The difficulty of clearly identifying disk features (spirals, bars, rings, etc.) in edge-on galaxies also makes it hard to see whether truncations might be related to specific morphological and dynamical features in the disk.

Pohlen et al. (2002), using very deep exposures of three face-on Sbc–Sc galaxies, showed that truncations can be clearly identified in face-on disks, and that the decline in surface brightness outside the truncation break is best described by an exponential, steeper by about a factor of two than that for the inner disk. Figure 1 shows an example of such a “classical” truncation. Despite the apparent prevalence of truncations at 3–5 scale lengths in edge-on galaxies (principally late-type spirals; e.g., Pohlen 2001; de Grijs, Kregel, & Wesson 2001; Kregel, van der Kruit, & de Grijs 2002), there *are* face-on or moderately inclined galaxies where the disk's surface brightness profile can be traced as a single exponential to larger radii without truncation (e.g. Barton & Thompson 1997; Weiner et al. 2001; Erwin, Pohlen, & Beckman 2005); Figure 1 shows an example.

In this Letter we draw attention to a significant subset (at least $\sim 25\%$) of barred S0–Sb galaxies which exhibit a kind of “anti-truncation”: the surface brightness profile becomes *shallower* at large radii, so that there is an excess of light above the outward projection of the (inner) exponential profile. While some of these profiles can be explained as light from a round outer envelope or halo (perhaps the outer extent of the bulge) dominating at larger radii, the majority cannot. Instead, they appear to be continuations of the disk with shallower but still exponential profiles. Some of these galaxies show strong asymmetries (e.g., lopsided or one-armed spirals) in the outer disk, and so may represent the result of recent interactions.

2. SAMPLE SELECTION AND DATA

The overall sample on which this study is based is described in more detail in Erwin (2005) and Erwin et al. (2005). Briefly, it consists of all northern ($\delta > -10°$), barred S0–Sb galaxies from the Uppsala Galaxy Catalog (Nilson 1973) with $D_{25} \geq 2.0'$, axis ratio $a/b \leq 2.0$ ($i \lesssim 60°$), and heliocentric $V \leq 2000$ km s^{-1} (measurements and classifications from de Vaucouleurs et al. 1991, hereafter RC3). Because there is evidence for inconsistency in Hubble types when spirals in the Virgo Cluster are compared with field spirals (e.g., Virgo Sa galaxies tend to resemble field Sc galaxies; Koopman & Kenney 1998), we excluded Virgo Cluster galaxies. (We did, however, include S0 galaxies from the Virgo Cluster, since there is no evidence for inconsistent classification of these galaxies.) After eliminating a few galaxies without bars (see Erwin 2005), we had a total of 65 galaxies.

The sample is complete within its selection criteria, but the diameter limit produces a bias in favor of luminous and high-surface-brightness galaxies. It is obviously biased against *unbarred* galaxies; but since we included both strong and weakly barred galaxies (SB and SAB

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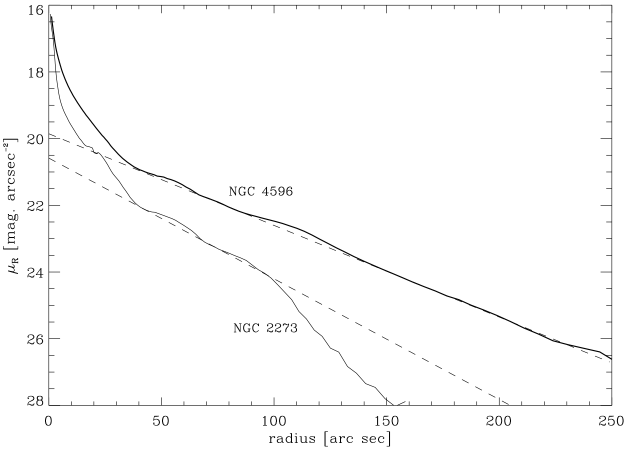

FIG. 1.— Truncated and untruncated surface-brightness profiles of barred galaxies: azimuthally averaged surface-brightness profiles for NGC 4596 (SB0) and NGC 2273 (SBa), along with exponential fits (dashed lines). NGC 4596 shows a Type I exponential profile extending to at least 5.7 scale lengths with no sign of a truncation; NGC 2273 shows a truncation at $r \sim 3.3$ scale lengths).

classifications from RC3), the result is representative of the majority of local, early-type disk galaxies.

We obtained azimuthally averaged, R-band surface brightness profiles of all the objects. Details of the observations, calibrations, and reduction procedures are given in Erwin et al. (2005). Particular attention was paid to ensuring flat and accurately subtracted sky backgrounds, with the halos of bright stars and neighboring galaxies carefully masked out. The orientation of the outer disk (position angle and projected ellpiticity) was derived from free-ellipse fits to the images, or from kinematic studies in the literature (see Erwin & Sparke 2003; Erwin 2005). The final profiles are from logarithmically spaced, concentric ellipses with constant position angle and ellipticity, matching that of the outer disk.

3. ANTI-TRUNCATIONS IN SURFACE BRIGHTNESS PROFILES

Figure 1 shows surface brightness profiles for two moderately inclined galaxies which exhibit "conventional" behavior: NGC 2273 shows a classical truncation at 3.3 scale lengths of the inner ($r \lesssim 95''$) disk, while NGC 4596 shows a single exponential profile which extends to at least > 6 scale lengths with no hint of a truncation. The majority of galaxies in our sample have similar profiles, with untruncated profiles being far more common (see Erwin et al. 2005 for the complete set of profiles).

At least 25% of the galaxies have profiles with qualitatively different behavior: there is an excess of light at large radii, above the projected exponential disk profile. The transition happens at surface brightness levels $\mu_R \sim 22.6$–25.6 mag arcsec^{-2} (mean = 24.1 ± 1.0; for comparison, the truncations in Pohlen et al. 2002 are at a mean $\mu_R = 24.6$). Figure 2 presents profiles for 12 of the 16 galaxies which unambiguously show this behavior (there are other galaxies which may have excess light at large radii, but S/N and sky-subtraction uncertainties make it more difficult to be certain). Because this is the opposite of a classical truncation — and happens at similar radii (3.2–6.0 inner scale lengths) — we dub them "anti-truncations"; by extending Freeman's (1970) classification scheme we can also refer to them as "Type III" profiles.

Because these are early-type galaxies (many of them S0), an obvious interpretation would be that the excess light at large radii is not from the *disk*, but rather from the luminous bulge or halo. This appears to be true for about one-third of the galaxies with anti-truncations (left-hand column of Figure 2) — all of them S0 — which have two characteristics in common. First, the inflection in the profiles is smooth and curved, which suggests that the outer light is from a separate component, added to the inner light from the disk. Second, the isophotes are elliptical in the inner region and become progressively *rounder* at larger radii (Figure 3a); this is clear evidence for an inclined disk embedded in a more spheroidal outer component.

But the majority of the galaxies (center and right-hand columns of Figure 2) have outer isophotes which are *not* significantly rounder than the inner isophotes (Figure 3b). Morphologically at least, the excess outer light is still part of the disk. In several of the Sab and Sb galaxies (e.g., NGC 4319, NGC 4699, NGC 5740, NGC 5806), symmetric or asymmetric spiral arms are clearly visible in the region outside the transition, which again argues for the excess outer light being part of the disk. Finally, in most of these profiles the transition is quite sharp, so we are probably not seeing the addition of light from two overlapping components, but rather a single disk with a fairly abrupt change in its density profile. The outer part of the profile is usually quite exponential; we show exponential fits to the outer profiles in Figure 2.

Could we be seeing thick disks, which are exponential but with larger scale lengths than the brighter thin disks? The combined profile of a thin disk and a thick disk should be the sum of two exponentials; observations of edge-on galaxies show that scale length ratios (thick to thin) are almost always less than 2.0 (Pohlen et al. 2004a). For some of our galaxies, particularly those with smooth transitions between the inner and outer regions, the profile is indeed well fit by a double-exponential (e.g., NGC 3489, 3941, and 4143). However, the resulting scale length ratios (outer to inner, or "thick" to "thin") range from 2.1 to 6.3, with a mean of 3.8, which is clearly outside the range of known thin/thick-disk systems. Furthermore, for the galaxies with the sharpest transitions (e.g., NGC 3982, 4371, 4691, and 5740), the best-fitting double-exponential produces a distinct excess above the observed profile in the transition region. We conclude that the outer excesses we see are probably *not* thick disks.

So what's going on? One clue may be the presence of lopsided/asymmetric spiral arms in the outer regions of some of the "disky" galaxies. NGC 4319 has a dramatic, one-armed outer spiral (responsible for the excess light between $50''$ and $100''$ in the profile; Figure 2) which may be connected to a faint structure further out resembling a tidal tail. NGC 5740 and NGC 5806 have weaker, lopsided spiral distortions in their outer isophotes. So one possibility is that interactions are responsible in some fashion for the outer excess light in the disks.

In two galaxies (NGC 4045 and NGC 4612), there are outer rings coincident with the transition between inner and outer slopes; in three more (NGC 4371, NGC 4699, and NGC 5806), the transition happens at $\sim$ 2–2.5 times the bar radius, which is the typical size of outer rings (e.g, Buta & Crocker 1993). This suggests that the transition might be happening at or near the bar's outer Lindblad resonance.

We note that in some galaxies (e.g., NGC 4612 and NGC 4699), the transition to the outer profile happens at a relatively small radius and high surface brightness level; since the outer disk is easily detected in these galaxies, it might be tempting to classify the inner exponential slope as the galaxy's "bulge" (the $r \lesssim 40''$ region of NGC 4699 is in fact referred to this way in Sandage & Bedke 1994). But these inner regions are where the bars (and, in NGC 4699, numerous spiral arms and dust lanes) are found and are thus *not* classical (kinematically hot) bulges; smaller central excesses (e.g., $r \lesssim 10''$ for NGC 4699) may be better candidates for the bulge proper. The inner disk regions of these two galaxies, at least, can thus be viewed as "pseudobulges" (e.g., Kormendy & Kennicutt 2004), albeit much larger than those pseudobulges thought to arise from bar-driven inflow, which are necessarily smaller than the bars.

These surface-brightness profiles with outer excesses, which we have termed anti-truncations or Type III profiles, are found in $\sim$ 25% of our sample; this should be regarded as a lower limit, since not all of our images reach the same limiting surface brightness and we could be missing similar features at fainter surface-brightness levels. Even if we exclude those galaxies whose isophote shapes indicate we are probably seeing luminous halos or outer bulges (left-hand column of Figure 2; 8% of the full sample, or 20% of the S0 galaxies), at least 17% of the galaxies appear to have disks with anti-truncation behavior. Disks with anti-truncations thus appear to be *more* common than disks with classical truncations ($\lesssim$ 12% of the sample; see Erwin et al. 2005), at least in barred, S0–Sb disk galaxies.

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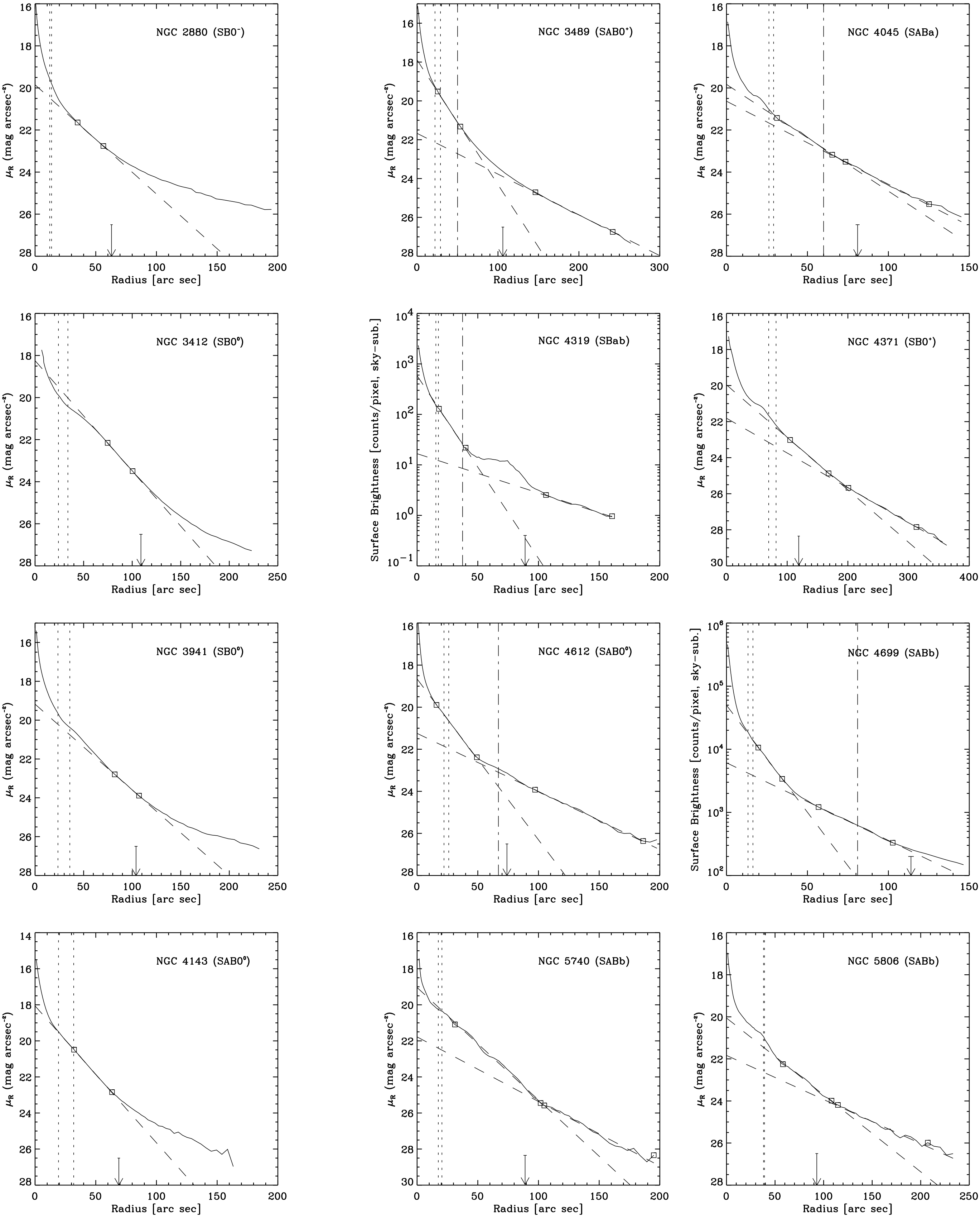

FIG. 2.— Type III ("anti-truncation") R-band surface-brightness profiles. *Left column*: Outer excess light is associated with halo/spheroid. *Center and right columns*: Outer excess light is probably part of the disk. Vertical dashed lines mark lower- and upper-limit measurements of the bar semi-major axis (deprojected); vertical dot-dashed lines indicate approximate size of outer rings, if any; and slanted dashed lines are exponential fits to regions of the profile delimited by the small squares. The small arrows indicate R_{25} (one-half of D_{25}). No photometric calibration was possible for NGC 4319 or NGC 4699.

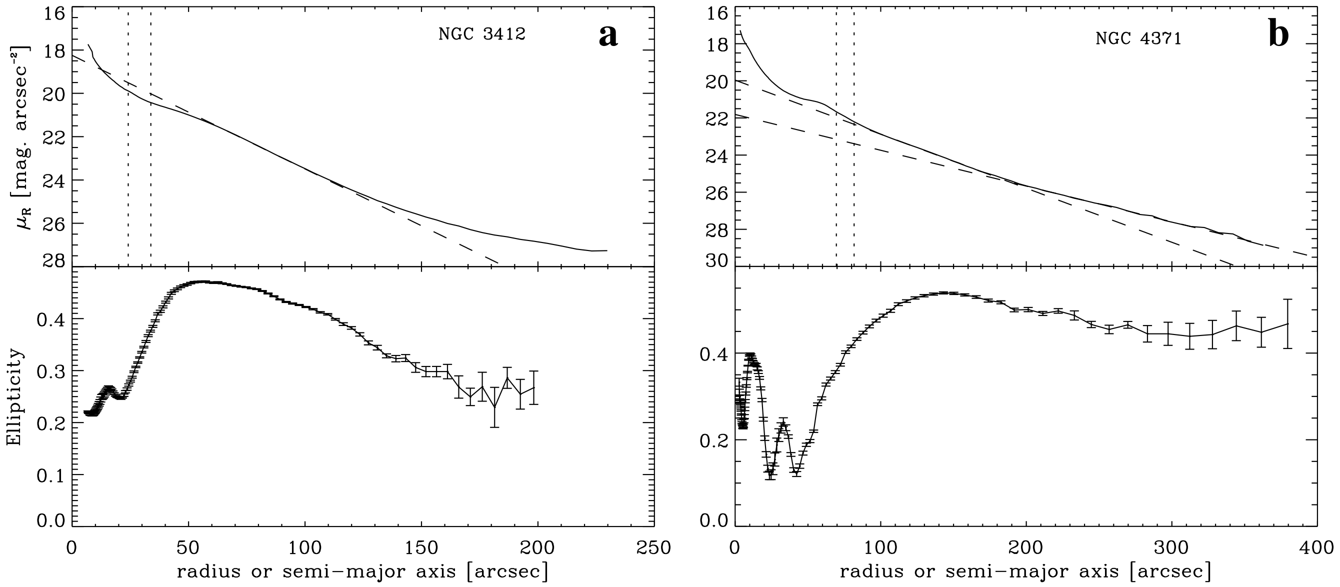

FIG. 3.— Azimuthally averaged surface-brightness profiles (top) and isophotal ellipticity profiles (bottom) for two galaxies with Type III profiles. **a.** NGC 3412 shows a clear "disk + spheroid" profile: the outer excess light ($r \gtrsim 120''$) is associated with isophotes which become progressively rounder at larger radii, consistent with the idea of a (projected) elliptical disk embedded within a rounder spheroid, e.g., a halo or outer bulge. **b.** NGC 4371 has outer isophotes ($r \gtrsim 190''$) with approximately constant ellipticity, roughly the same as the inner isophotes, so the excess light at $r \gtrsim 190''$ is probably part of the disk.