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Evidence for a large stellar bar in the Low Surface Brightness galaxy UGC 7321★

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Abstract. Late-type spiral galaxies are thought to be the dynamically simplest type of disk galaxy and our understanding of their properties plays a key role in galaxy formation and evolution scenarios. The *low surface brightness* (LSB) galaxy UGC 7321, a nearby, isolated, "superthin" edge-on galaxy, is an ideal object to study these purely disk-dominated bulge-less galaxies. Although late type spirals are believed to exhibit the simplest possible structure, even prior observations showed deviations from a pure single component exponential disk in the case of UGC 7321. We present for the first time photometric evidence for peanut-shaped outer isophotes from a deep optical (*R*-band) image of UGC 7321. Observations and dynamical modeling suggest that boxy/peanut-shaped (b/p) bulges in general form through the buckling instability in bars of the parent galaxy disks. Together with recent HI observations supporting the presence of a stellar bar in UGC 7321, this could be the earliest known case of the buckling process during the evolutionary life of a LSB galaxy, whereby material in the disk-bar has started to be pumped up above the disk, but a genuine bulge has not yet formed.

Key words. galaxies: spiral – galaxies: structure – galaxies: fundamental parameters – galaxies: evolution – galaxies: peculiar – galaxies: individual: UGC 7321

1. Introduction

Nearly all disk galaxies have both a stellar disk and a bulge. Traditionally, bulges were seen as similar to small ellipticals: kinematically hot, spheroidal or triaxial, and old. Therefore, they probably formed during the first collapse of the protocloud or at least in an early stage of their evolution. Multicolor studies of highly inclined galaxies (e.g. Balcells & Peletier 1994; Peletier et al. 1999) support this picture for early-type disk galaxies: their bulges have ages similar to cluster ellipticals, although they also tend to be bluer than ellipticals of similar luminosity. However, there are galaxies which do not have a bulge component. These pure disk galaxies show clearly that the bulge formation is not a necessary outcome of the early galaxy formation process.

Other possible origins of bulges are merger scenarios where either a small satellite galaxy is accreted and spirals into the center of the pre-existing disk (Aguerri et al. 2001) or where two equal mass galaxies (Kauffmann et al. 1996) merge and form an elliptical structure. Later, this object again accretes gas, which builds the present day surrounding disk. Another currently favoured scenario is the bulge growth by bar-driven mass inflow. Starting with a pure disk galaxy, numerical simulations have shown that the disks are, almost always, unstable against bar formation. The existing bar is then able to move material into the center. A buckling vertical instability pumps the stars above the disk, resulting in a three-dimensional bulge-like object (e.g. Friedli & Martinet 1993). The growing central mass eventually weakens and dissolves the bar (Norman et al. 1996; Sellwood & Moore 1999). Thus we are left with an unbarred disk galaxy possessing a spheroidal bulge as observed today. In this scenario, pre-existing spheroidal bulges would become contaminated by disk stars, which might explain why bulges and the inner parts of disks have similar colour (Balcells & Peletier 1994).

Bars are associated with the appearance of the so-called box- or peanut-shaped (b/p) "bulges" visible in edge-on disk galaxies. The b/p part of these bulges are almost certainly the resonant off-plane thickening of a bar (Combes et al. 1990;

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Table 1. Properties of UGC 7321. Note: Distance and M_B taken from Matthews (2000). Other values from RC3 (Third Reference Catalogue of bright galaxies: de Vaucouleurs et al. 1991).

Property	Value
Hubble type	Sd
T	7.0 ± 0.8
$cz_{\rm helio}$ [km s^{-1}]	408 ± 6
Distance [Mpc]	10 ± 3
Scale [pc/arcsec]	48.5
M_B [mag]	−17.1

Raha et al. 1991; Pfenniger & Friedli 1991; Patsis et al. 2002a). The connection between bars and b/p bulges has been observationally verified by gas kinematics (Kuijken & Merrifield 1995; Bureau 1998), and Lütticke et al. (2000b) found a significant correlation between b/p bulges and bar signatures seen in cuts along, and parallel to, the major axis in NIR images.

Photometrically observed peanut-shaped contours therefore provide evidence for the thickening process caused by the buckling instability.

In this paper, we analyze the case of UGC 7321, a nearly edge-on Sd galaxy. Global properties of this galaxy are given in Table 1. UGC 7321 does not have a prominent bulge as one can infer from its contour map (Fig. 1). However, the outer isophotes in deep *R*-band images show peanut-type distortions. UGC 7321 provides a useful case for studying the origin of peanut-type isophotal distortions in a galaxy without a prominent bulge. It could provide clues to the very early phases of formation of a central dense component. A key question is whether the galaxy harbours a bar. UGC 7321 was studied in detail in a series of papers by L. Matthews (Matthews et al. 1999; Matthews 2000; Matthews & Wood 2001). Matthews et al. (1999) found a red nuclear feature in the *B*–*R* colour map of UGC 7321, only a few arcseconds across, and raised the possibility that it could be a kinematically distinct disk subsystem analogous to a bulge.

The existence, definition, and properties of bulges in late-type spiral galaxies were recently described by Böker et al. (2003). Late-type bulges are far from uniform and care needs to be taken regarding what may rightfully be called a bulge. Our analysis (Sect. 3) shows that, if the peanut distortions are indeed the result of a bar, the inferred bar length is uncomfortably long as compared to other late-type galaxies. However, alternative origins for the peanut distortions, discussed in Sect. 4, fail to provide convincing explanations.

2. Data

Images of UGC 7321 were obtained during an observing run in May 2001 at the 2.2 m telescope of the Calar Alto observatory (Spain) equipped with CAFOS. The dithered observations of this edge-on galaxy were used as night sky flatfields for the original face-on imaging study without losing dark time for flatfields and are now discussed here. The data reduction is described in detail in Pohlen et al. (2002a) and only briefly recalled here. The images were taken in a special *R*-band filter showing a nearly rectangular filter characteristic combined with a high peak efficiency. Landolt standard fields (Landolt 1992) were observed to achieve a photometric calibration to the standard Johnson system (cf. Pohlen et al. 2002a). During the data reduction process, special emphasis was given to performing the crucial flatfielding and sky subtraction. The final image used for this study is a combination of six stacked 600 s exposures, which allows one to reliably trace the profiles and contours down to $\mu \approx 27.2\,R\text{-mag}/\square''$.

3. Results

A contour map of the inner 120″ of UGC 7321 (*R*-band) is shown in Fig. 2. The six outer isophotes clearly deviate from pure ellipticity, with a depression along the minor axis above and below the galaxy center. According to Lütticke et al. (2000a), this depression along the minor axis is the characteristic feature of a classical, type 1 peanut-shaped distortion. The presence of peanut-shaped distortions is made obvious in cuts parallel to the major axis. In Fig. 3 we show such cuts at 0″, ±6″, ±12″ and ±18″. The peanut-shape signature (the central "dip" in the profile) is visible in the ±12″ and obvious in the ±18″ profiles. The maximum peanut distortion occurs around ±40″ from the center.

The term "peanut-shaped distortion" is commonly used to describe a property of the galaxy's bulge. Here, however, the galaxy clearly lacks a kinematically hot, spheroidal $R^{1/4}$ system, and appears to lack a "pseudobulge" (Kormendy 1993) or "exponential bulge" (Carollo et al. 1998); we show below that the galaxy has little central light in excess of the best-fit disk exponential model. Therefore, the peanut-shaped distortion in UGC 7321 seems to be a property of the galaxy's disk.

Given the absence of a strong central light concentration, we model the light distribution of UGC 7321 as a pure disk with the following hypotheses: the face-on surface brightness profile is exponential with scalelength $h_{\rm in}$, out to a break radius $R_{\rm br}$, and again exponential outside $R_{\rm br}$, with an outer scalelength $h_{\rm out} < h_{\rm in}$. The vertical surface brightness profile is also taken to be exponential, with scaleheight z. We employ a slightly modified version (cf. Pohlen 2001) of the three-dimensional fitting routine described in Pohlen et al. (2000) to derive a best-fit model of the galaxy's isophotes.

Radial profiles of the resulting model overplotted on the data are shown in Fig. 3. The best-fit parameters are: inner scalelength $h_{\rm in} = 79.2''$, mean break radius $R_{\rm br} = 136.5''$ (+135.0″and −138.0″), outer scalelength $h_{\rm out} = 15.5''$, and vertical scaleheight $z = 19.7''$. Assuming a distance of 10.0 Mpc, this yields $R_{\rm br} = 6.6$ kpc, $h_{\rm in} = 3.8$ kpc, and $z = 1.0$ kpc. The three-dimensional modeling allows for a rather precise determination of the galaxy's inclination in nearly edge-on views. We derive an inclination of $i = 88.5°$, a central surface brightness of $\mu_0 = 21.3\,R\text{-mag}/\square''$ and $\mu_{\rm br} = 23.5\,R\text{-mag}/\square''$ at the break radius. The corresponding face-on values are: $\mu_0 = 23.8\,R\text{-mag}/\square''$ and $\mu_{\rm br} = 25.7\,R\text{-mag}/\square''$. A contour plot of the model light distribution is shown in Fig. 2. Comparison of the two panels in Fig. 2 shows that the standard horizontal- and vertical-exponential disk model lacks the outer peanut

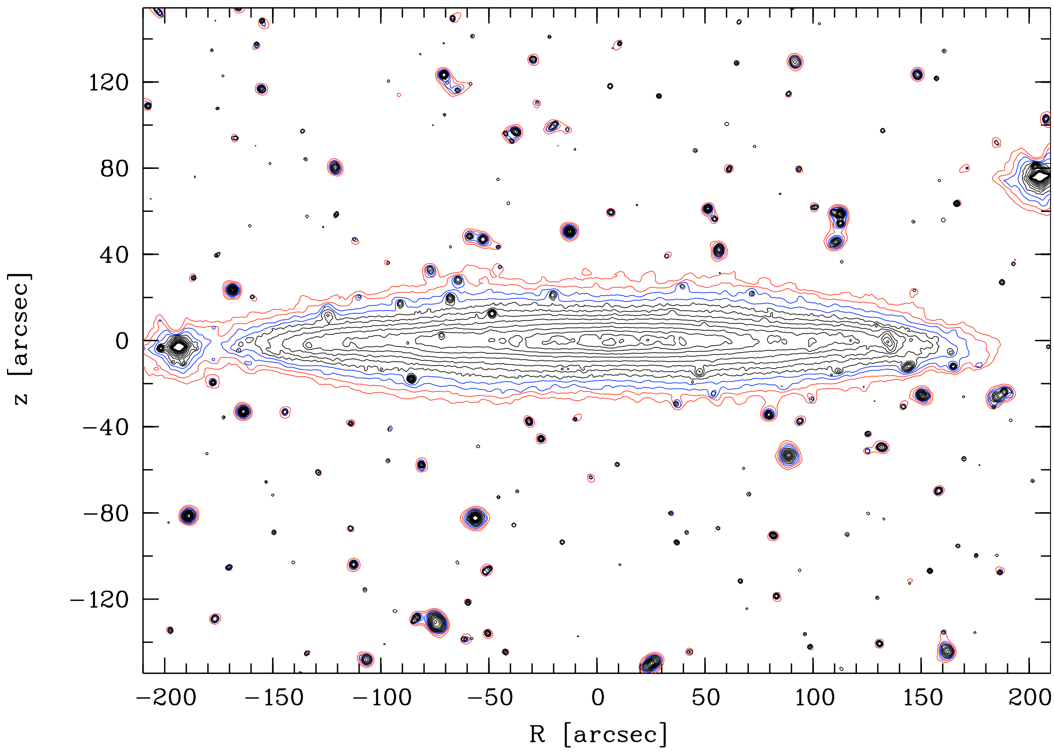

Fig. 1. Contour map (μ_R) of UGC 7321 from 26.7 to 18.7 equally spaced by 0.5 mag.

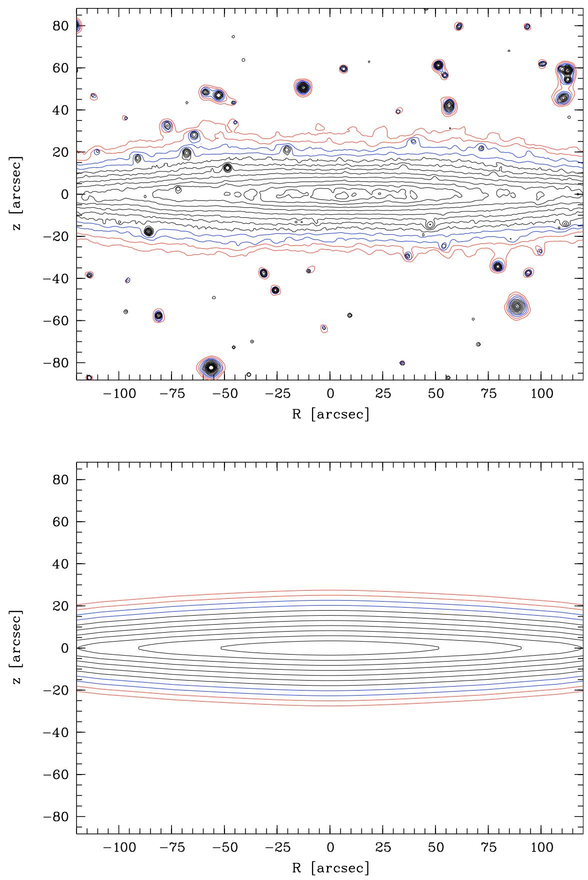

Fig. 2. *(Upper panel)* The inner 120″ of UGC 7321 to highlight the region of the peanut distortions. *(Lower panel)* isophotal contours of the three-dimensional model described in the text. Contours from 26.7 to 18.7 are equally spaced by 0.5 mag.

distortions seen in UGC 7321. Figure 3 shows model cuts parallel to the major axis overplotted on the corresponding cuts for UGC 7321. Here again, the peanut distortions in the data at $R \lesssim 50''$ deviate from the model in the lowest, outermost two cuts ($z = \pm 12''$, $z = \pm 18''$). Two further aspects are worth emphasizing. First, the good match in the outer parts between data and model provides evidence that UGC 7321, like other LSB galaxies (Pohlen et al. 2002b), has the truncated, two-slope disk structure found in high-surface brightness spirals (cf. Pohlen et al. 2002a). Second, the major-axis cut (top profile in Fig. 3) shows a central enhancement over the best-fit exponential model at $\pm 40''$. This structure indicates that an additional component exists besides the double-exponential light distribution in UGC 7321. This component is affected by the in-plane dust extinction on the order of 0.4 mag (Matthews & Wood 2001). Using a simple-minded definition of bulges as any excess light over the inward extrapolation of the exponential disk profile (e.g. Carollo et al. 1999), we could call the inner excess "the bulge" of UGC 7321. Interestingly, the radial position of the peanut distortions ($\approx \pm 50''$) is comparable to the radial extent of the inner brightening, suggesting a parallel with the isophotal structure of classical box-peanut bulges (cf. Lütticke et al. 2000b).

Alternatively, the inner brightening of the major-axis profile might trace a bar in UGC 7321. Its profile and radial extent are hard to infer from the major-axis profile given the extinction by dust. The properties of such a bar might be inferred from the peanut distortions if we assume that the peanut feature is produced by the resonant off-plane thickening of a bar (e.g. Combes et al. 1990). Following Lütticke et al. (2000b), we derive the length of the peanut structure (BPL = 83″) as the

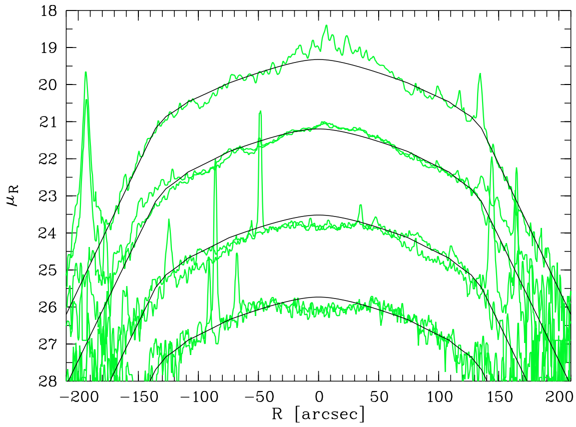

Fig. 3. Radial surface brightness profiles of UGC 7321: Major axis (top) and three parallel profiles at 6″, 12″, and 18″ above and below the major axis. For better visibility the four profiles are shifted by (−2, −1, 0, +1) mag, respectively.

radial distance between the maxima of the peanut distortion (in detail: −39″ and +44″) measured in radial cuts.

For a sample of normal HSB galaxies, Lütticke et al. (2000b) find a mean value of 2.7 ± 0.3 for the ratio of projected bar length (BAL) to BPL. Assuming a similar scaling, the projected length of the bar in UGC 7321 would be ≈224 ± 25″ in diameter and 112 ± 13″ in radius. The two extreme values for the same sample (BAL/BPL = 2.2 or 3.2) would allow projected bar radii in the range of 91″ to 133″.

The estimated bar length is quite large. It is comparable to the total galaxy diameter, and would indicate that most of the body of UGC 7321 comprises a bar seen side-on with a ratio of bar length to galaxy size of BAL/D_{25} = 224/302 = 0.7 (D_{25} ≡ observed 25 mag/□″ *B*-band diameter uncorrected for inclination, from Matthews et al. 1999). In comparison, for a sample of normal disk galaxies observed in the NIR, Lütticke et al. (2000b) derive a mean value of BAL/D_{25} = 0.4 ± 0.2. D_{25} is probably not a good indicator for comparing LSBs with normal disk galaxies, but any inclination correction for D_{25} will increase the ratio BAL/D_{25} even more.

The numbers given above depend somewhat on the precise definition used for bar length and peanut length. Lütticke et al. (2000b) define the beginning of the bar in radial profiles as the location where the bar extends above the extrapolated outer disk. If bars are defined to start at their shoulders or bumps, BAL will be a factor of 1.3 smaller. In addition, using the full structure of the peanut rather than the maximum, BPL will be also a factor of 1.2 larger. This results in BAL/BPL = 2.1 or even BAL/BPL = 1.7, which is closer to the value obtained in *N*-body simulations (Pfenniger 1984). For any of the given definitions, the case remains that the inferred bar length for UGC 7321 is quite large.

Comparing BAL with the radial scalelength (h) instead yields a ratio of BAL/h = 224/79 = 2.8. Even assuming the lowest measured BAL/BPL ratio of 2.2 from Lütticke et al. (2000b), BAL/h will still be 182/79 = 2.3. This is comparable to a bar of an early type galaxy. Erwin (2003) derives a mean value of BAL/h = 2.4 ± 1.0 for a sample of face-on S0 to Sab galaxies and obtained a ratio of BAL/h = 1.2 ± 0.5 for Sd galaxies taken from a sample of Martin (1995). Another example is the edge-on Sb galaxy NGC 2424. It exhibits a ratio of BAL/h = 2.6, taking BAL = 76 from Lütticke et al. (2000b) and h = 29 from Pohlen (2001)[1]. Note that the apparently unknown orientation of a bar in an edge-on galaxy is restricted by the actual peanut appearance of the contours. Lütticke et al. (2000b) have shown that the bar-produced b/p structure appears peanut-shaped only for a small range of aspect angles between 77°–90° for the associated bar, assuming a galaxy inclination of 90°.

UGC 7321 is classified as a non box/peanut-shaped (b/p) bulge (type 4) in the catalogue of Lütticke et al. (2000a) and is actually the first Sd galaxy with a peanut bulge. However, they classify "bulges" to be either elliptical (4), boxy (3+2), or peanut-shaped (1), and therefore concentrate only on the inner part of UGC 7321 (which is indeed type 4) visible in DSS (Digitized Sky Survey) images. The peanut structure here is much larger than for a typical galaxy with a b/p-bulge. In addition, the characteristic angle θ between the major axis and the radial ray passing through the maximum of the peanut distortion is much smaller than normal (cf. Lütticke 1999; Shaw et al. 1990). For UGC 7321, θ is ≈18° while the mean value for all galaxies with peanut-shaped bulges is 39° ± 10° with a minimum of 31° (Lütticke 1999). The conclusion would be that we are seeing an edge-on bar without the additional (superimposed) spheroidal bulge component as is typical for earlier (S0-Sc) galaxy types. Therefore, this large, slightly peanut-shaped, outer structure is *the bar* and one has to consider that the term b/p-bulge is a combination of a b/p structure, which we have here, and a spheroidal bulge component.

4. Discussion

Inferring the presence of a bar from the weak isophotal distortion observed in UGC 7321 might be controversial, especially given the implied large bar size compared to the galaxy disk. Here, we examine what other evidence exists for or against the presence of the bar, and what other configurations may create the observed peanut distortion.

Strong support for our photometric bar detection comes from the recent analysis of HI-data for UGC 7321 by Uson & Matthews (2003). They find that the major axis position-velocity (P–V) profile shows a clearly visible "figure-of-eight" structure (cf. their Fig. 10). This is typical for a barred galaxy viewed edge-on (Kuijken & Merrifield 1995). Uson & Matthews (2003) favour the explanation proposed by Brinks & Shane (1984) that this feature may also result from the warping and flaring of its HI disk. However, there is only a very mild – compared to other later type galaxies (García-Ruiz et al. 2002) – HI warp on the west side[2]. Uson & Matthews (2003) assign a decrease in the HI intensity at ≈−25″ to the possible presence of a small bar extending from about −30″ to +40″

[1] The scalelength h is determined only one-dimensionally and is therefore just a lower limit. In the worst case it is off by a factor of +20% compared to the true 3D scalelength (cf. Pohlen 2001), which allows a BAL/h as high as 3.3 for NGC 2424.

[2] Here: positive side.

which nicely coincides[3] with our "bulge" feature in the major axis light profile. Nevertheless, if this is a bar it would be too small to account for the peanut-shaped outer structure. We do not find indications of a flaring in the *stellar* disk. By introducing a flaring in our model we confirm that it could not be responsible for the observed peanut distortion in the inner part. The effect of a radially increasing scaleheight is most prominent towards the edges of the disk.

Binney & Petrou (1985) and Whitmore & Bell (1988) have shown that the accretion of satellite galaxies is a possible formation process for b/p bulges. For normal b/p-bulges these scenarios are excluded due to the overwhelming evidence for bar-driven evolution (e.g. Bureau 2002; Lütticke et al. 2000b), where the role of interaction is only to trigger the bar itself. However, Lütticke et al. (2003) found a special class of thick boxy bulges (TBB) which suggest a merger origin. These galaxies are often disturbed, frequently showing prominent irregularities and asymmetries, and possess significantly more projected satellites compared to a control sample. All these characteristics are in contrast to UGC 7321's smooth and undisturbed disk and its unusually isolated environment. There are no signs for a recent merger event, such as an increase in starformation, asymmetric dust distribution, arcs, shells, filaments, or a strong stellar warp. Uson & Matthews (2003) estimate that a possible encounter $\approx 10^9$ years ago of UGC 7321 with its closest neighbour could be responsible for the observed mild HI warp.

Taken together, nearly all of the observational evidence points against a merger scenario. The peanut-shaped structures found in simulations (e.g. Hernquist & Quinn 1989) resemble typical early-type spirals and S0s such as NGC 128, IC 4767, or HCG 87A and are often located in dense groups; some of them are even "hybrid" scenarios where the bar is triggered by a merger (e.g. Mihos et al. 1995).

Patsis et al. (2002a), analysing *N*-body models, describe a new vertical resonance producing an edge-on "boxy" or "peanut" structure for non-barred galaxies. However, the examples from the *N*-body simulation have only an oval distortion as their main morphological feature and could be characterized morphologically as S0 galaxies. In addition, their model allows boxes, but not strong peanuts or X-shaped structures.

Therefore, the presence of a large bar extending over the main body of the galaxy provides the best explanation for the peanut-shaped contours in UGC 7321 and the measured "figure-of-eight" pattern in the recent HI measurements.

A bar, especially one as big as we photometrically infer, in a low surface brightness galaxy, a system expected to be dark-matter dominated, could solve the problem that many rotation curves of LSB galaxies cannot (e.g. de Blok & Bosma 2002) be fitted by the cuspy halo profiles predicted by CDM cosmogonies. Specifically, Swaters et al. (2003) discuss non-circular, bar-induced kinematics as the source of deviations between rotation curve-based mass models and the NFW-type CDM halos. Weinberg & Katz (2002) propose that a dark matter cusp might be removed due to dynamical interaction of the halo with the bar. However, several works argue against such a mechanism and in favor of non-circular kinematics to explain the deviations. For example, Mayer & Wadsley (2003) used high resolution *N*-Body/SPH simulations to address the question of bar formation and evolution in LSB galaxies. They conclude that LSB disks may go bar-unstable in gas-rich disks embedded in low-concentration halos. However, the resulting bars are too short and probably of too low angular momentum content to affect the inner halo density profile. They also conclude that a bulge-like component must be present in any LSB galaxy that has become bar unstable. In the case of UGC 7321 the inner component could be tracing this process, so that we are observing just the beginning of the morphological evolution from its first bar into a bulge-like central structure, according to the secular evolution scenario.

[3] Note: We use a different orientation of the image.

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