THE ASTROPHYSICAL JOURNAL, 583:L75–L78, 2003 February 1
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NGC 4608 AND NGC 5701: BARRED GALAXIES WITHOUT DISKS?

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Received 2002 August 23; accepted 2002 December 23; published 2003 January 8

ABSTRACT

We have performed for the first time in the literature a two-dimensional structural analysis on the barred lenticular and face-on galaxies NGC 4608 and NGC 5701. The results indicate that either these galaxies have never had large disks or their disks were almost completely destroyed by their strong bars because of secular evolution processes. We discuss these surprising conclusions, checking for signs of secular evolution, considering bar-forming instabilities, and suggesting, based on *N*-body simulations, a new mechanism to form bars in spheroids, which includes nonspherical halos. Quantitative predictions from our new mechanism are compared with those from other recent models for bar formation and evolution.

Subject headings: galaxies: evolution — galaxies: halos — galaxies: individual (NGC 4608, NGC 5701) — galaxies: structure — methods: *n*-body simulations

1. INTRODUCTION

The most widely accepted mechanism to produce bars in galaxies is based on a global instability in cool stellar disks, in which cool means rotationally supported (see, e.g., Binney & Tremaine 1987). However, it was already argued by Toomre (1981) that a high central density disk would not form a bar, since an inner Lindblad resonance (ILR) would stop the bar instability (Sellwood 2000). There are nevertheless several evidences for the presence of dense centers and ILRs in galaxies, including barred ones (Sellwood 2002). Recently, Sellwood & Moore (1999) have numerically confirmed that even dynamically cool disks cannot develop a bar if it has the observed high central densities. Thus, how galaxies form bars remains a question to be properly answered. Possibilities are discussed in the papers by Sellwood cited above, but all are easily rejected in the same papers. The problem is even worse for lenticular galaxies, since these are not cool stellar systems and, generally speaking, have the most massive bulges among disk galaxies in the Hubble sequence. But the existence of barred lenticulars is indisputable. For instance, in the Revised Shapley-Ames Catalog (Sandage & Tammann 1981), one-fourth of the lenticular galaxies brighter than 14 in the *B* band are barred. A related issue concerns the role in bar formation of halos, which were once thought to stabilize disks against the formation of a bar. Recent results, however, indicate that, while producing smaller growth rates of bar-forming modes, halos can induce stronger bars (Athanassoula 2002 and references therein). In this Letter, we present results of a detailed structural analysis on two barred lenticulars, which indicate that either their disks have almost completely disappeared, probably by secular evolution processes, or bars were formed without disks. Moreover, we present numerical simulations that show how the latter possibility can be attained with nonspherical halos.

2. STRUCTURAL ANALYSIS

The two galaxies discussed in this Letter were observed in optical (*B*, *V*, *R*, *I*) and near-infrared (K_s) broad bands in the Steward Observatory 61 inch and Bok telescopes, respectively. After standard reduction procedures, the images were used in a two-dimensional structural analysis algorithm developed by de Souza (1997). The algorithm was constructed in order to model the surface brightness profiles of galaxies using two components: a bulge obeying the Sérsic luminosity profile and an exponential disk. Besides being thoroughly tested in model galaxies, the algorithm already has been applied in a sample of 39 Sbc galaxies (Gadotti 1999; S. dos Anjos & D. A. Gadotti 2003, in preparation) and 51 ellipticals and lenticulars (R. E. de Souza, D. A. Gadotti, & S. dos Anjos 2003, in preparation), providing valuable structural information.

The reader is referred to the above cited references for details on the algorithm. Essentially, the galaxy images are transformed into a matrix in which each point represents a pixel value. The user provides initial values for the structural parameters of bulge and disk (e.g., effective surface brightness, ellipticity, Sérsic index, etc.), and the algorithm then tries to fit the galaxy image with model images of bulge and disk by varying their structural parameters, minimizing the χ^2 deviation at each pixel until it reaches a convergence limit. A total of 11 parameters are needed to fully describe the model, and these are obtained from the image fitting. Using the fitted parameters, one can build a model galaxy and construct a residual image that can be useful in showing hidden substructures.

An important point to clarify now is that in the case of strongly barred galaxies, such as those studied here, the code performs a decomposition in two components that can be thought of as the bar/bulge and the disk. The reader should keep this in mind when we refer to "bulge" hereafter.

NGC 4608 is cataloged as a SB0 galaxy in the Revised Shapley-Ames Catalog (Sandage & Tammann 1981) and by van den Bergh, Pierce, & Tully (1990) with CCD images. Previous surface photometry analysis was done by Benedict (1976), with one-dimensional fitting on shallow photographic plates, and by Wozniak & Pierce (1991), fitting ellipses to the isophotes on CCD frames. Both studies concluded that this galaxy presents a low surface brightness disk. NGC 5701 is described as having an intermediate morphological type between SB0 and SBa by a number of authors (see, e.g., Sandage & Tammann 1981).

When applied to NGC 4608 and NGC 5701, the algorithm retrieves a *very* low surface brightness disk. The major component is indubitably represented by the bar/bulge. Thus, one is left to conclude that there is practically no disk present in these galaxies. The presence of a large Freeman disk such as the ones

observed in spirals can be readily discarded. Figure 1 shows the two galaxies and their residual images after subtraction of the model images. The direct images at left have an isophotal map overlaid with a 0.5 mag interval between each contour level. These images refer to the *R* broad band, but similar results were obtained in all the other bands. It is worth noting that not even in K_s was a disk found, which could be a possibility if the disk was hidden by dust or contained mostly very old population stars. Our surface photometry reaches the level of about 26 mag arcsec^{-2} in *B* and 23 mag arcsec^{-2} in K_s, with comparable values reached in the other passbands. Thus, our photometry is deep enough to indicate that the absence of a disk is real. Even a faint disk would be detected. If there is a disk in these galaxies, it must have a luminosity far lower than the one measured in normal S0 galaxies. Moreover, we do detect disks in other galaxies with images taken during the same nights, with the same exposure times and applying the same analysis.

Looking at the images at left in Figure 1, one can already note what seems to be a somewhat empty region around the bar in both galaxies. These empty regions appear much clearer in the residual images at right. In the case of NGC 4608, the residual image shows clearly the bar and the lens. For NGC 5701, one is left with the bar, the outer ring, and the inner ring, which is not visible in the direct image. The important point to stress here is that after the subtraction of only a bulge model, there is no clear sign of the presence of a disk. We should remark that these objects are genuine S0 galaxies, as many authors have argued, because the conspicuous bars *should* be a disk perturbation. Thus, one must face the possibility of formation and maintenance of a bar in the almost total absence of a disk.

Another possibility is that secular evolutionary processes induced by bars in their host galaxies (Gadotti & dos Anjos 2001 and references therein) have disturbed the structure of an originally healthy normal disk. In principle, these strong bars could have transferred material from the initial disk to the bulge. Then, what now seems to be a lens in NGC 4608 could be the outer remains of the disk. The outer ring in NGC 5701 also could be the signature of a preexistent disk. For this galaxy, too, there is a hint of inner disk remaining in the residual image.

To test the evolutionary hypothesis, we may consider the question of whether the stars we see today in the bar once belonged to a disk. Could the luminosity we detect in the bar make up a disk if distributed accordingly? To answer that, we have determined the luminosity in all bands within a radius equal to the bar length (that was determined by examining the ellipticity and position angle radial profiles) for the direct and residual images. The difference between them corresponds to the bulge luminosity, while the luminosity in the residual images may be attributed to the assumed disk. Thus, we calculated what would have been a bulge/disk luminosity ratio for these galaxies before the secular evolution processes took place. This ratio is $\approx$2, and therefore, it is compatible with the secular evolution hypothesis, since the bulge/disk ratio for normal S0 galaxies is around 2 (Binney & Merrifield 1998).

While bar formation without disks seems to be a quite unusual possibility, it is not at all trivial that secular processes can be so strong as to destroy a disk almost completely. We suggest, in the next section, how bars could be formed in galaxies without disks.

3. *N*-BODY SIMULATIONS

The idea of having a bar forming without a disk is very powerful, given its simplicity. It is based on the assumption that

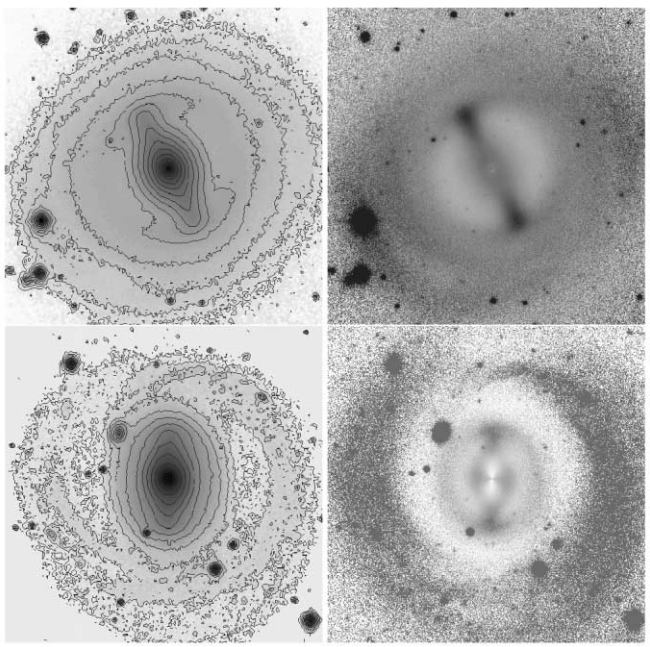

FIG. 1.—Results from the structural analysis. Top panels refer to NGC 4608, while bottom panels refer to NGC 5701. At left we present direct *R* images with an isophotal map. At right we show residual images after the subtraction of a bulge model only. Note the absence of a disk.

nonspherical dark matter halos should exist. As noted by Frenk (1988), model dark halos are generally triaxial and may be prolate. Moreover, their axial ratios can be quite extreme, reaching values around 3, while a ratio of 2 is common. Given that these halos are large and massive, it is reasonable that they could exert a strong influence on the dynamics of a stellar system that is embedded in such a halo. We performed numerical simulations to check if such a configuration could make a spheroid turn into a bar, i.e., a triaxial (or prolate) eccentric structure.

Thus, we simulated the evolution of a Plummer sphere embedded in a rigid halo represented by a logarithmic potential, which produces flat rotation curves and can be used to easily modify the halo core radius, the mass within it, and the halo ellipticity (Binney & Tremaine 1987). The Plummer sphere has a characteristic radius of 2 kpc, extends to 17 kpc, and has a total mass of $1.2 \times 10^{11} M_{\odot}$. The halo parameters modified were the axial ratios (from 1 to 4, prolate and triaxial), the core radius (from 6 to 10 kpc), and the core mass (from 0.9×10^{11} to $1.2 \times 10^{11} M_{\odot}$). These values for the core properties are usually found in the literature (e.g., Begeman, Broeils, & Sanders 1991).

The simulations were performed with the NEMO package (Teuben 1995) with 10^5 particles, using the Barnes & Hut (1986) algorithm. The softening parameter was $\simeq$0.03, and the opening angle was 0.7. Energy and the center of mass were conserved better than 0.1%, typically.

Several experiments were performed varying the halo parameters. We noted that (1) the sphere is stable when the axial ratios are low, remaining approximately spherical for any typical values for the core radius and mass; (2) oval distortions and weak and strong bars are formed when raising the axial ratios from $\approx$2 to $\approx$4, not depending substantially on the other core parameters; and (3) these results do not depend on whether the halo is prolate or triaxial. Figure 2 shows a clarifying example. It shows how a Plummer sphere can be transformed into a bar within the dynamical influence of a triaxial halo with an axial ratio that equals 3, after 1 Gyr. Comparing Figure 2 with the left panels of Figure 1, one can see that the bar formed

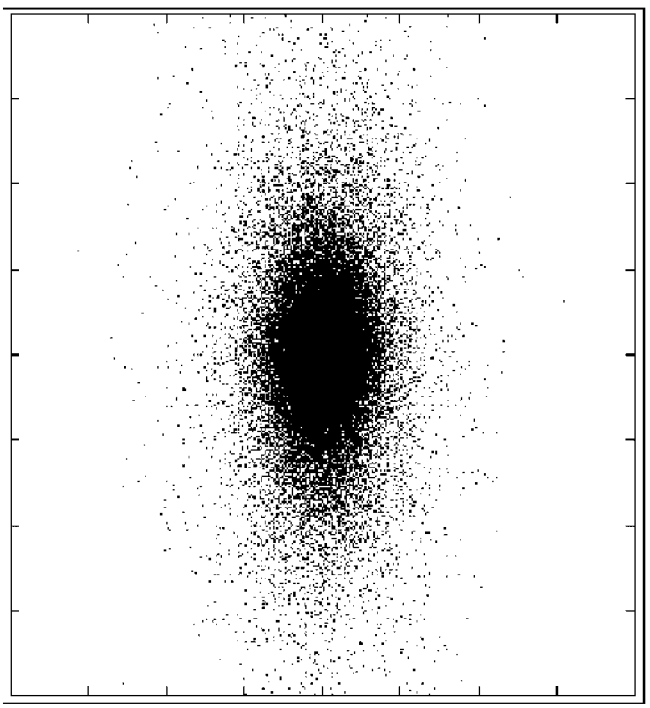

FIG. 2.—Final structure formed from a Plummer sphere under the dynamical influence of an eccentric halo after 1 Gyr. Compare with the bars in the left panels of Fig. 1.

in our simulations is a good representation of the bars in NGC 4608 and NGC 5701. Also, the size of the bars in these galaxies and in our simulations is similar (≈10 kpc).

Our new bar formation mechanism needs halos with axial ratios around 3, and the results from cosmological simulations by Frenk (1988) indicate that at least some halos must have these high values for their axial ratios. More recent cosmological simulations by, e.g., Warren et al. (1992) show that the axial ratios of halos have a wide distribution going to values as high as 3, while the simulations of Bullock (2002) indicate a typical value of around 1.5 but with extreme values going as high as 5. Concerning observations, recent results indicate values ranging from 1.25 to 2 (Buote et al. 2002; Sackett 1999) to more than 3 (Sackett & Sparke 1990).

4. DISCUSSION AND CONCLUSIONS

There are thus two possible scenarios that could explain the existence of bars in systems (almost) devoid of disks. The first one is that bars can form in diskless systems, as described in the previous section. The second one is that such systems are extreme examples of the evolutionary scenario proposed recently by Athanassoula (2003). A weak bar forms initially and grows by losing angular momentum to the external disk and the halo, via resonant stars (see Athanassoula 2002; Athanassoula & Misiriotis 2002). In extreme cases, it could "consume" all or most of the disk material, so that the end product would be a bar in a halo, with very little, if any, disk left, i.e., what we have found for NGC 4608 and NGC 5701. Thus, these galaxies can well be extreme examples of this evolutionary scenario. With this mechanism, strong halos lead to strong bars, which is also the case.

Let us now evaluate the predictions of Athanassoula's model (ATH) and our model of bar formation without disk (GDS) and make a quantitative comparison with the results for NGC 4608 and NGC 5701. For that, snapshots of the final result from both

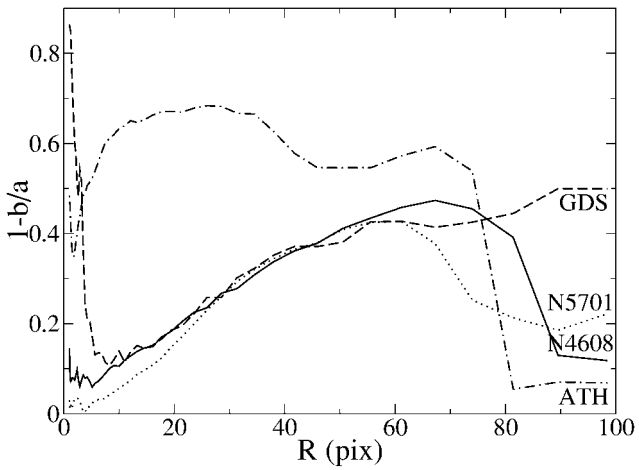

FIG. 3.—Ellipticity radial profiles for NGC 4608 and NGC 5701, as well as for both the GDS and the ATH models.

models were scaled in size and intensity to allow for a meaningful comparison with the observed galaxies. Figure 3 shows radial profiles of the ellipticity of the two galaxies and of both models. One sees that GDS provides a very good fit to the galaxies in most of the profile, while ATH fits reasonably well to only the last fifth part of it. Figure 4 presents intensity cuts along the major and minor axes of the bar in the models and the galaxies. One can see that these cuts are better predicted by the ATH model. Another strong point favoring the secular evolution hypothesis is the fact that a boxy-peanut shape develops in the ATH model when viewed edge-on, as we know is the case for many observed bars (e.g., Bureau & Freeman 1999). This does *not* occur in the GDS model.

Another powerful quantitative comparison of the face-on shapes can be performed if one calculates the Fourier components of the intensity distribution projected onto the equatorial plane, such as in, e.g., Athanassoula & Misiriotis (2002). Figure 5 shows the results of the Fourier analysis. An inclination angle of 15° was assumed for both galaxies to be deprojected before the components were calculated, in agreement with values found in the literature (Jungwiert, Combes, & Axon 1997) and from analyzing single-dish H I velocity measurements (Haynes et al. 1998). The main difference between the behavior of the Fourier components in the ATH and the GDS models is that there is a maximum in the former but not in the

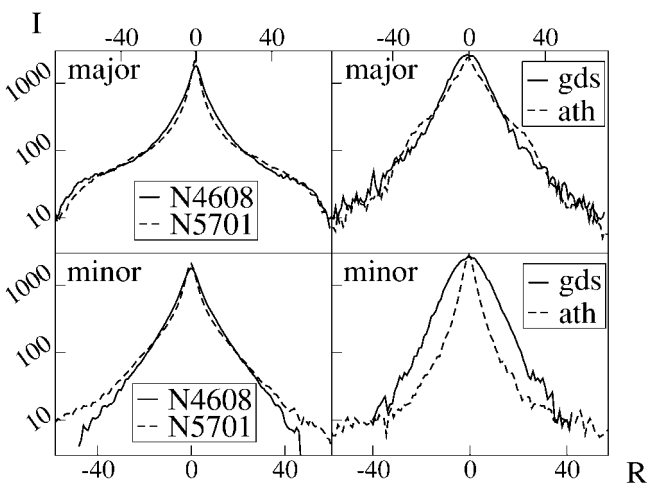

FIG. 4.—Intensity profiles along the major and minor axes of the observed galaxies and the models.

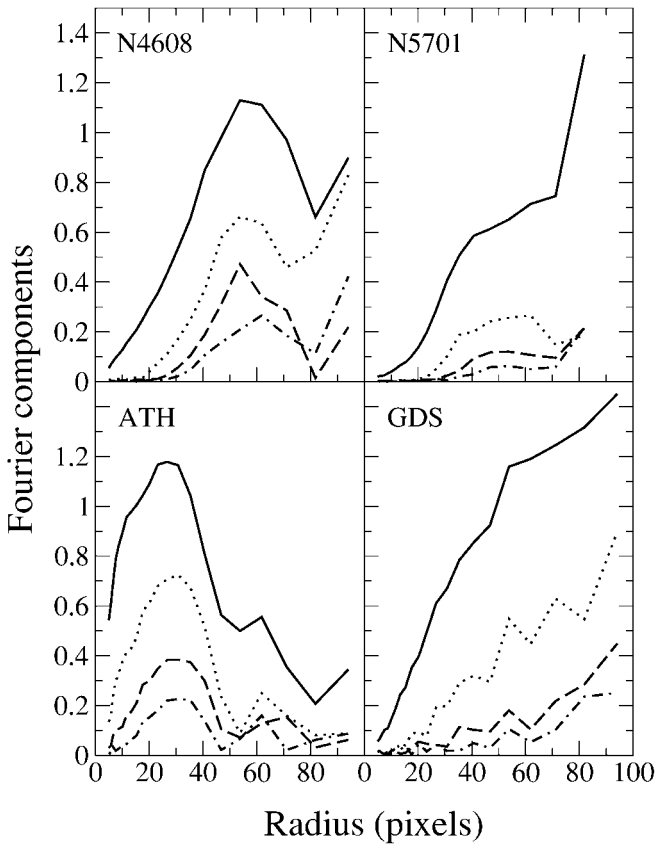

FIG. 5.—Radial profiles of the Fourier components of the observed galaxies and the models. The solid line refers to $m = 2$, while the dotted line refers to $m = 4$, the dashed line to $m = 6$, and the dash-dotted line to $m = 8$.

latter. Thus, the data from NGC 4608 favors the ATH model. The position of the maximum is not relevant here, since it varies considerably from one simulation to another, depending on the Q Toomre parameter (see, e.g., Binney & Tremaine 1987). The maximum is nearer to the center in dynamically cold systems (E. Athanassoula 2002, private communication). However, NGC 5701 does not seem to have a maximum, which supports the GDS model, unless a maximum is found in a *very* deep image. The reader must bear in mind that both models are in no way a specific fit to the galaxies under study, but they show that extreme cases of barred galaxies with hardly any disk are possible. It is clear that a definite conclusion should not be taken at this stage. More data (including spectroscopy) are necessary on these two galaxies and S0 galaxies in general. On the other hand, simulations can now be directed to address this question further.

Nonetheless, two not necessarily mutually exclusive conclusions can be tentatively postulated: (1) bars can be formed in spheroids through the dynamical effects of a sufficiently eccentric halo, without the need of a stellar disk, and (2) secular evolution in barred galaxies can be strong enough to almost completely destroy their disks.

The first possibility puts some hope in our struggle to understand how bars form in galaxies, since other mechanisms have several serious drawbacks. Of course, this mechanism alone cannot be responsible for all the observed bars, since it needs very eccentric halos (and there are disk galaxies), but it could be at least for some barred lenticulars. Also, it does not exclude the possibility of other bar-forming instabilities acting together and thus can be explored to overcome some of the difficulties. On the other hand, it is based on very simplistic numerical experiments. More realistic simulations can be performed, e.g., including a live halo and gas, which can then account for other observed substructures, such as the rings in NGC 5701. However, the essential idea, which we show here, seems to be correct. The second possible conclusion shows how strong secular evolutionary processes may be and, therefore, how seriously they should be considered in models of galaxy formation and evolution.

We are indebted to the referee, Lia Athanassoula, for many suggestions and comments that helped to greatly improve our work and for letting us use her results prior to publication. It is a pleasure to thank Ron Buta and Ivo Busko for help on deprojecting galaxy images and Fourier analysis. D. A. G. would like to thank Peter Teuben for invaluable help on NEMO. Financial support from FAPESP grant 99/07492-7 is acknowledged.

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