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Exponential bulges and antitruncated disks in lenticular galaxies

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Abstract. The presence of exponential bulges and anti-truncated disks has been noticed in many lenticular galaxies. In fact, it could be expected because the very formation of S0 galaxies includes various processes of secular evolution. We discuss how to distinguish between a pseudobulge and an anti-truncated disk, and also what particular mechanisms may be responsible for the formation of anti-truncated disks. Some bright examples of lenticular galaxies with the multi-tiers exponential stellar structures are presented, among them – two central group giant S0s seen face-on and perfectly axisymmetric.

Keywords: galaxies: elliptical and lenticular, cD; galaxies: bulges; galaxies: disks; galaxies: evolution

1. Introduction

Bulges have been traditionally thought to have de Vaucouleurs' brightness profiles just as elliptical galaxies (e.g. Freeman 1970). However John Kormendy (Kormendy 1982a, Kormendy 1982b, Kormendy 1993) has proved that there exists a type of bulges named 'pseudobulges' which resemble disks from the dynamical point of view: they are rather cold and demonstrate fast rotation. Despite their dynamical properties, they are bulges from the geometrical point of view: they are 'fat' and have rather large scaleheights. Pseudobulges are thought to be products of secular evolution; but if it is so, then dynamical simulations (e.g. Pfenniger & Friedli 1991) predict that they must have exponential brightness profiles. And indeed, small bulges of late-type spirals which could be easily made by secular evolution, practically all have exponential brightness profiles (e.g. Andredakis et al. 1995, Graham 2001). But it is not only small bulges in late-type spirals that have exponential brightness profiles. Lenticular galaxies whose bulges are not usually small at all demonstrate typically the mean Sersic coefficient lesser than Sa galaxies, and often their $n < 2$: the Sersic parameter n peaks at the Sa–Sb morphological type and falls further toward S0s (Graham 2001, Laurikainen et al. 2005, Laurikainen et al. 2007). In fact, it is quite natural because the very event of a S0 galaxy transformation from a spiral must include various processes of secular evolution resulting in matter re-distribution over the radius and bulge reshaping.

But galactic disks outside the bulges can also consist of several exponential segments. Now it becomes clear that so called anti-truncated disks consisting of two exponential segments with the outer scalelengths larger than the inner ones, may be the dominant type of galactic disks among some types of galaxies (Erwin et al. 2008a). We reported finding a few large nearby spiral galaxies with such two-tiers disks during the last 10 years. A significant population of such disks has been found since the brightness profiles begin to reach 27th and 28th magnitudes from one square arcsecond (Pohlen & Trujillo 2006). Does it mean that the outer segments of anti-truncated disks represent always low surface-brightness (LSB) disks? The statistics by Erwin et al. (Erwin et al. 2008b) for barred galaxies says so. Among our findings in unbarred spiral galaxies, only one galaxy, NGC 5533, has a LSB outer disk (Sil'chenko et al. 1998). Other galaxies (NGC 7217, Sil'chenko & Afanasiev 2000; NGC 615, Sil'chenko et al. 2001; NGC 4138, Afanasiev & Sil'chenko 2002; NGC 7742, Sil'chenko & Moiseev 2006) have on the contrary quite normal outer disks, if to compare with the Freeman's (Freemen 1970) reference value of the central B surface brightness of 21.7; and simultaneously they have compact bright inner disks. Can we distinguish the compact inner disk from a pseudobulge? Yes, by using multi-variant approach. For example, in NGC 7742 all spirals and current star formation are confined to the inner exponential disk, and the outer one is smooth and featureless (Sil'chenko & Moiseev 2006), so we can conclude that the inner exponential stellar component is dynamically cold and cannot be a bulge. But the key property is a visible geometry of the stellar component with the exponential profile. To be a disk, it must be thin. For disks inclined to the line of sight, a good check is isophotal analysis. The outer disk is always assumed to be thin: then its isophote axis ratio characterizes the cosine of the inclination. If the inner component has the same visible axis ratio as the outer one and if two disks are coplanar, the inner structure cannot be a spheroid, it must be a disk. For face-on galaxies, this approach does not work: their isophotes are always round independently of the scaleheights. But for face-on galaxies we can use kinematical data and estimate their thickness by measuring vertical stellar velocity dispersions.

We have now started a program of studying systematically multi-tiers (anti-truncated) exponential structures in early-type, presumably lenticular, galaxies. The study will include photometric as well as spectral observations. Some first results are presented in this talk.

2. Observations

The photometric observations the results of which we discuss here have been made with the focal reducer SCORPIO of the Russian 6m telescope (Afanasiev & Moiseev 2005) in the direct-image mode. The CCD detector EEV 42-40 with the size of 2048 × 2048 has been used in binned mode of 2 × 2. The field of view was about 6 arcminutes, the scale was 0.35 arcsec per binned pixel. The photometric observations have been undertaken on August 21, 2007, under the seeing quality of about $2''$. We have exposed 5 fields in the NGC 80 group and 6 fields in the NGC 524 group, through two filters, B and V. The exposure times were selected in accordance with the surface brightness of the targets observed; for example, we exposed NGC 524 itself during 60 sec in the B-filter and during 30 sec in the V-filter. As a flat field, we used the exposures of the twilight sky. The calibration onto the standard Johnson BV system has been made by using multi-aperture photoelectric data collected by HYPERLEDA for NGC 80 and NGC 524.

3. Photometric structure of the central group S0 galaxies

Two central group galaxies under consideration are typical giant lenticular galaxies, with the blue absolute magnitudes of about $-21.6 - -21.7$ (HYPERLEDA). Both are very red, $(B-V)_e = 1.07$, and are seen face-on, $b/a > 0.9$.

We have calculated azimuthally averaged surface brightness profiles for NGC 524 in two filters, B and V. The data are rather precise, and we trace the profiles up to $R = 80''$, or about 10 kpc from the center, with the accuracy better than 0.01 mag. At larger radii the accuracy is worse due to bright stars projected onto the galaxy. When compare our V-profile with the model decomposition proposed by Baggett et al. (Baggett et al. 1998) (Fig. 3), namely, with a single de Vaucouleurs' bulge approximation, one can see that

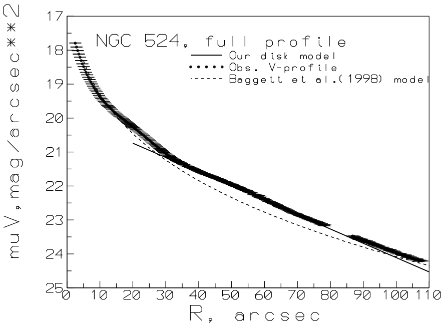

Figure 1. The V-band azimuthally-averaged brightness profile of NGC 524 obtained by us with the reducer SCORPIO at the 6m telescope; the model decomposition proposed by Baggett et al. (1998) is overlaid. One can see that the high-accuracy data do not agree with a single de Vaucouleurs' bulge model; instead at least two exponential components are needed.

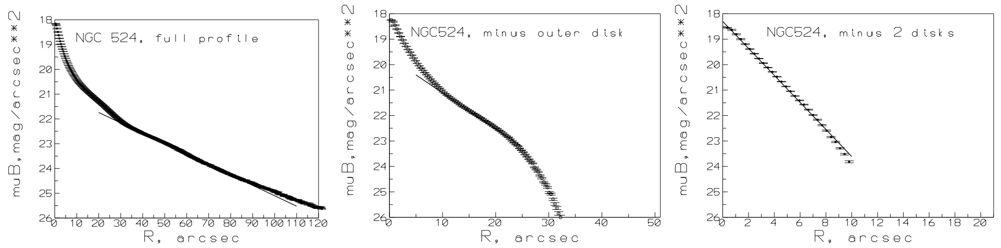

Figure 2. The B-band azimuthally-averaged brightness profile of NGC 524 obtained by us with the reducer SCORPIO at the 6m telescope can be decomposed step-by-step into three exponential components.

Table 1. Parameters of the photometric components of NGC 524 approximated by an exponential law

Component	Radius range of the fit	μ_0, mag/□″	h''	h, kpc
		B-filter		
Outer disk	$34'' - 90''$	20.906 ± 0.007	26.07 ± 0.06	3.02
Inner disk	$10'' - 23''$	19.67 ± 0.01	7.67 ± 0.05	0.89
Bulge	$1'' - 8''$	18.25 ± 0.01	2.04 ± 0.01	0.24

their model is inappropriate. Instead we see at least two exponential components: the 'outer' one in the radius range of $R = 35'' - 90''$ and the 'inner' one in the radius range of $R = 10'' - 25''$. We fit the outer part of the surface brightness profile by an exponential law, construct a 2D model image of this disk and subtract it from the full image observed. For the residual image, we calculate again the azimuthally averaged surface brightness profile, fit its outer part by an exponential law, construct the 2D image of the inner disk and subtract it from the first-step residual image. Interestingly the brightness profile of the second-step residual image which is safely traced up to $10''$, is also exponential (Fig. 2)! Figure 2 presents all steps of our decomposition procedure, and in the Table 1 we give the parameters of the exponential stellar substructures obtained by this procedure.

Figure 3 presents the $B - V$ colour profile of the first-step residual image (the inner disk). It reveals a net colour difference between the inner disk, $R > 10''$, and the 'bulge', $R < 10''$. This colour difference, $\Delta(B - V) = 0.07$, may be resulted from a metallicity

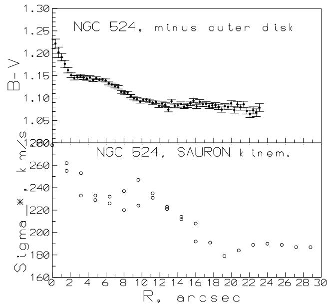

Figure 3. The comparison of the azimuthally averaged profiles of the $B - V$ colour calculated from the residual image of NGC 524 after the subtraction of the outer disk and of the stellar velocity dispersion demonstrating a break at the edge of a dynamically hot bulge.

difference of 0.2 dex under the old stellar age $T = 12$ Gyr, or on the contrary from an age difference of 8 Gyr under the metallicity of [Z/H]= +0.1 (Worthey 1994, and also his WEBsite, Dial-a-Galaxy option), the inner disk being younger or/and more metal-poor. We have compared the colour profile of the residual image with the stellar velocity dispersion profile similarly averaged in the rings over the map obtained from the SAURON data (Emsellem et al. 2004, see also the WEBsite of the SAURON project) (Fig. 3). The profiles of the colour and of the stellar velocity dispersion are qualitatively similar! Certainly, we see a transition from the (exponential) bulge to the inner disk at $R \approx 10''$. Preliminary estimates of the scaleheight of the inner disk in NGC 524, by treating the measured line-of-sight stellar velocity dispersion as a vertical one, have given a value of about 1.5 kpc; it is a typical scaleheight of a thick stellar disk which can be expected in a lenticular galaxy.

The very similar surface brightness profile consisting of two exponential disks and of a very compact bulge has been observed by us earlier in the giant lenticular galaxy NGC 80, which is also settled at the center of a rich X-ray group (Sil'chenko et al. 2003). With the new observations, we confirm certainly this multi-tiers structure. In both galaxies the outer stellar disks are quite normal as concerning their scalelengths or their central surface brightnesses, and the inner disks are compact and bright. Both galaxies are seen face-on and are certainly unbarred; the low ellipticity of their isophotes over the full radial extension proves that the galaxies are strictly axisymmetric. If the exponential inner stellar structures have been formed by secular evolution, where are signatures of the main 'driver' of secular evolution, of a bar?

4. What can be the mechanisms to form anti-truncated disks in lenticular galaxies?

It seems clear that anti-truncated disks are to be a result of matter re-distribution along the radius of a disk galaxy, and the very event of re-distribution must be rather fast and discrete. Several candidate mechanisms can be proposed. Younger et al. (Younger et al. 2007) simulates a minor merger, and they obtain an anti-truncated stellar disk in the merger remnant, mainly due to stellar diffusion from the inner part of the initial spiral galaxy into an outer region. In such model the outer part of the multi-tiers stellar disk in the merger remnant seems to be a low surface brightness disk. Some years ago I proposed another mechanism where a transient interaction, due to, say, by-pass of a rather massive galaxy, provokes intense gas inflow and results in gas concentration in the very inner part of a galaxy with the subsequent star formation burst. In the frame of this model, the inner disk must be more bright and compact than the usual large-scale stellar disks of spiral galaxies are. We may expect that an observational statistics of the parameters of inner and outer exponential disks in the anti-truncated galaxies would help to select a model.

In the group NGC 80, besides the central galaxy, we have analysed brightness profiles in more 10 lenticular galaxies, with the absolute blue magnitudes from –17 to –20. Among those, 7 S0s have appeared to possess two-tiers exponential disks. And among 7 S0 galaxies with the two-tiers disks, three have the inner compact disks and the outer normal disks, and four have the inner normal disks and the outer LSB ones. Together with NGC 80 itself and with NGC 524, with their inner compact bright disks and extended normal ones, we obtain half-to-half preliminary statistics which implies that the origin of the multi-tiers exponential disks may be different in different galaxies.

5. Conclusions

If we assume that multi-tiers exponential profiles are formed by secular evolution of galactic disks, the best place to search for them would be lenticular galaxies. Lenticulars galaxies had to reform secularly their stellar disks during their transformation from S to S0; hence S0s must be the hosts of both multi-tiers disks and pseudobulges. To select a particular mechanism of forming anti-truncated disks, we must know better the statistics of their properties which are not still collected over representative samples. Among the possible alternatives of the origin of multi-tiers exponential profiles there are minor merger versus tides (but the same alternative exists for the origin of S0s beyond clusters!). To choose, we need to know a balance between compact+normal and normal+LSB stellar disk combinations.

Secular redistribution of stars and other matter in disks is thought to be made by bars: bars are usually generated by any interaction and even without interactions – by intrinsic instabilities. But almost all our galaxies with the multi-tiers disks are unbarred; the face-on S0s NGC 524 and NGC 80 are perfectly axisymmetric. And the samples of Erwin et al. (Erwin et al. 2008a, Erwin et al. 2008b) imply the same conclusion: among barred galaxies, the anti-truncated disks contribute one third of all, among unbarred – more than 50%. This inconsistency is a complete puzzle yet.

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References

Afanasiev, V.L. & Sil'chenko, O.K. 2002, *AJ* 124, 706
Afanasiev, V.L. & Moiseev, A.V. 2005, *Astronomy Letters* 31, 194
Andredakis, Y.C., Peletier, R.F., Balcells, M. 1995, *MNRAS* 275, 874
Baggett, W.E., Baggett, S.M., Anderson, K.S.J. 1998, *AJ* 116, 1626

Emsellem, E., Cappellari, M., Peletier, R.F., et al. 2004, *MNRAS* 352, 721

Erwin, P., Pohlen, M., Beckman, J.E., Gutiérrez, L., Aladro, R. 2008, in: J.H. Knapen, T.J. Mahoney, & A. Vazdekis (eds.), *Pathways through an Eclectic Universe. ASP Conf. Ser. v. 390* (San Francisco), p. 251

Erwin, P., Pohlen, M., Beckman, J.E. 2008, *AJ* 135, 20

Freeman, K.C. 1970, *ApJ* 160, 811

Graham, A.W. 2001, *MNRAS* 326, 543

Kormendy, J. 1982, in: L. Martinet & M. Mayor (eds.), *Morphology and Dynamics of Galaxies, Twelfth Advanced Course of the Swiss Society of Astronomy and Astrophysics* (Sauverny: Geneva Obs.), p. 113

Kormendy, J. 1982, *ApJ* 257, 75

Kormendy, J. 1993, in: H. Habing & H. Dejonghe (eds.), *Galactic Bulges. IAU Symp. 153* (Dordrecht: Kluwer), p. 209

Laurikainen, E., Salo, H., Buta, R. 2005, *MNRAS* 362, 1319

Laurikainen, E., Salo, H., Buta, R., Knapen, J.H. 2007, *MNRAS* 381, 401

Pfenniger, D. & Friedli, D. 1991, *A& A* 252, 75

Pohlen, M. & Trujillo, I. 2006, *A& A* 454, 759

Sil'chenko, O.K., Burenkov, A. N., Vlasyuk, V.V. 1998, *New Astronomy* 3, 15

Sil'chenko, O.K. & Afanasiev, V.L. 2000, *A& A* 364, 479

Sil'chenko, O.K., Vlasyuk, V.V., Alvarado, F. 2001, *AJ* 121, 2499

Sil'chenko, O.K., Koposov, S.E., Vlasyuk, V.V., Spiridonova, O.I. 2003, *Astronomy Reports* 47, 88

Sil'chenko, O.K. & Moiseev, A.V. 2006, *AJ* 131, 1336

Worthey, G. 1994, *ApJS* 95, 107

Younger, J.D., Cox, T.J., Seth, A.C., Hernquist, L. 2007, *ApJ* 670, 269