Proc. IV Serbian-Bulgarian Astronomical Conference,
Belgrade 21–24 April 2004,
eds. M. S. Dimitrijević, V. Golev, L. Č. Popović, M. Tsvetkov,
Publ. Astron. Soc. "Rudjer Bošković" No 5, 2005, 175 - 181 *Contributed paper*

DECOMPOSITION OF PROFILES OF GALAXIES WITH CONVEX DISK SHAPES

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Abstract. An improved one-dimensional decomposition technique for galactic profiles is presented. Both bulge and disk shapes are modeled by the Sersic (1968) formula and for the disk shape a second order term is included. The optimal free parameters - central brightness, scale length and exponential number, are derived by iterative procedure in the spirit of Kormendy (1977). The method is applied on published profiles of some nearby galaxies. Earlier (Georgiev, 2004; Georgiev and Stanchev, 2004) have found that the disk shapes of the early type galaxies are more convex, with central depression, while the disk shapes of the later type galaxies are close to exponential form of Freeman (1970). In the present work we show that the use of a second order term in the Sersic formula occurs an useful tool for detection of disks with ring-like shapes. Such disks are shown here in the cases of the galaxies IC 4871 and ESO 416-G25, that have edge-on orientation, as well as in the cases of the galaxies 7 Zw 793 and M 51, with almost face-on orientation.

1. INTRODUCTION

Freeman (1970) has introduced the exponential model of the radial disk profiles as a first approximation, known till now as the "Freeman's law". It is considered that the exponential shape could be understood from theoretical point of view (Freeman, 1970; Mo et al., 1998; Reshetnikov, 2000). However, the deep CCD profiles of the galactic disks show convex or truncated shapes and the Freeman's law is a very rough approximation. Generally, the truncation of the surface brightness in the outer part of the disk could be explained by decreasing of the star forming rate, due to insufficient matter concentration or/and lack of reasons for disk instabilities (Bottema, 1993; Geressen et al., 1997; Bizyaev and Zasov, 2002).This phenomenon is not studied completely yet, but the convex disk shapes should be modeled for the studies of the galaxies. The model of the truncated shape of the disk profile is introduced by van der Kruit and Searle (1981) and applied widely by Barteldrees and Dettmar (1994) by means of a special parameter – a cut-off radius. However, when the deepness of the observation increases, the cut-off radius increases too. By this reason Pohlen et al. (2000) have introduced a presentation of the disk shape with two exponents: inner, corresponding to the Freeman's law, and outer, more steeper. The deep observations

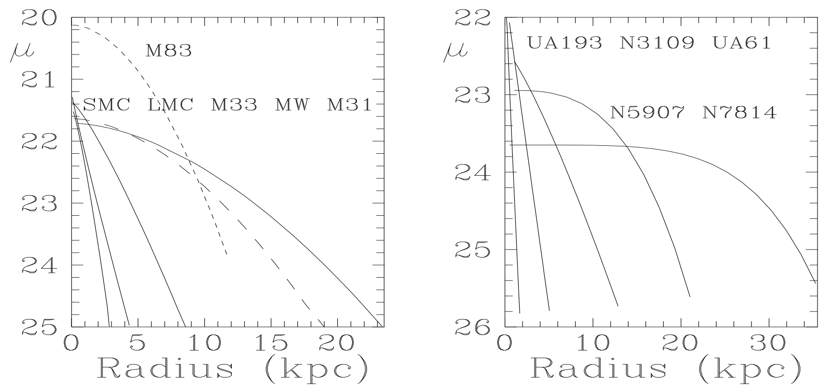

Figure 1: The disk shapes of nearby galaxies, modeled by the Sersic (1968) formula: **Left panel**: B-band radial disk profiles of the nearby galaxies (from the left to the right) SNC, LMC, M 33, and M 31, (solid curves), as well as the mass profile of the Milky Way with arbitrary ordinate shift, (long dashed curve) and B-band profile of the barred galaxy M 83 (short dashed curve) (Gerogiev, 2004); **Right panel**: B-band major axis profiles of five edge-on galaxies (from the left to the right) UGCA 193, NGC 3109, UGCA 61, NGC 5907 and NGC 7814, given with solid curves (Georgiev and Stanchev, 2004).

of 3 face-on galaxies, up to 29 mag/arcsec^2 in the R band of Pohlen et al. (2002) supported this "double exponent model".

Generally, the shape of the bulge changes smoothly with the Hubble type of the galaxy (Andredakis et al., 1995; Bagget et al., 1988; Chiotti and Bertin, 1999; Graham, 2001; Simard et al., 2002; Balcels et al., 2003). However, the changes of the disk shape with the Hubble type or with the mass of the disk are investigated poorly (van der Kruit, 2002) and what could be the reason is the lack of an adequate model of the observing profile of the disk. Another possibility for description of the disk shapes is the applying of a smooth model of the convex shape of the disk. In our previous papers (Georgiev, 2004; Georgiev and Stanchev, 2004) we have shown that the disk profiles could be modeled by means of the Sersic (1968) formula. It is applied in an iterative decomposition procedure in the spirit of Kormendy (1977), where both bulge and disk shapes are modeled by the Sersic equation. The number of the iteration is usually from 2 to 7.

Examples of nearby galaxies and edge-on galaxies are presented in Fig. 1.

The disk shapes are presented after correction to galactic extinction and reduction to absolute dimensions. It is found that in both cases the shape of the profile depends on the size or luminosity, i.e. on the mass of the disk. When the mass increases (toward the early spirals) the curvature of the radial disk profiles increases and the central peak of the disk brightness decreases. When the mass decreases (toward the late spirals and irregulars) the profile tends to be exponential with well prominent central peak.

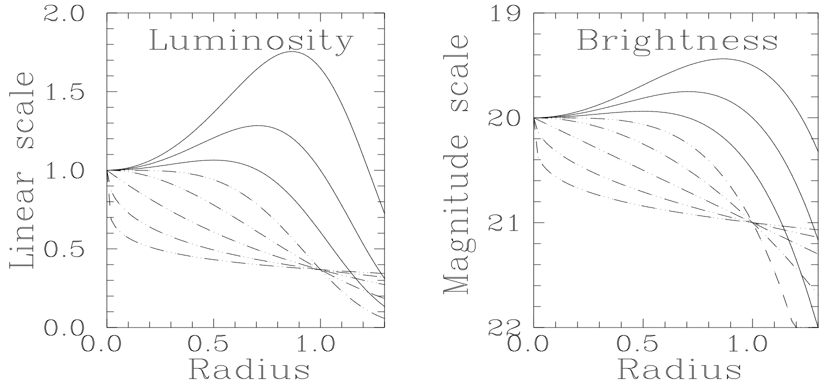

Figure 2: Shapes of radial profiles of bulges or disks, modeled by means of the Sersic formula of 1^{st} order for 5 values of n: 0.25, 0.5, 1, 2 and 4 (dashed curves, from left to the right, respectivelly) and 3 examples of 2^{nd} order Sersic formula (solid curves): **Left panel**: in the linear scale of the intensities; **Right panel**: in the magnitude scale of the brightness with arbitrary zero point.

However, the nature of the galactic disks seems more complicated: some of the disks of the early spirals seem to be rings (Kormendy, 1977). By this reason we have introduced more flexible modeling of the convex disk profiles, using "second order Sersic formula". In the present paper we give examples of this approach.

2. GENERALIZATION OF THE SERSIC FORMULA

In our previous papers (Georgiev, 2004; Georgiev and Stanchev, 2004) we have generalized the Sersic formula adding 2^{nd} and 3^{rd} order terms, calling the results "second order" and "third order" Sersic formulas. The full (3^{rd} order) formula could be written in two forms: in the linear scale, i.e. in intensities I_r, or in the magnitude scale, i.e. in surface brightness, μ_r:

$$\begin{aligned} I_r &= I_0\, exp\left[-\left(\frac{r}{h_1}\right)^n - \left(\frac{r}{h_2}\right)^{2n} - \left(\frac{r}{h_3}\right)^{3n}\right] \\ \mu_r &= \mu_0 + C_1 r^n + C_2 r^{2n} + C_3 r^{3n} \end{aligned} \quad (1)$$

The usual 1^{st} order Sersic formula is a particular case of Eq. 1. It contains only the first term and it has 3 free parameters - the central intensity I_0 (or the central surface brightness $\mu_0 = -2.5 \log I_0$), the scale length $h_1 = (1.0857/C_1)^{1/n}$ and the exponential number n, which describes the curvature of the profile. Notice that usually the exponential number n is noted as $1/n$, but following Lauberts and Valentijn (1989) we prefer the notation, which has more simple interpretation. The 1^{st} order Sersic formula could represent various shapes of profiles. The case $n = 1/4$, which is known as "1/4 law" of de Vaucouleurs (1959), describes the profiles of the

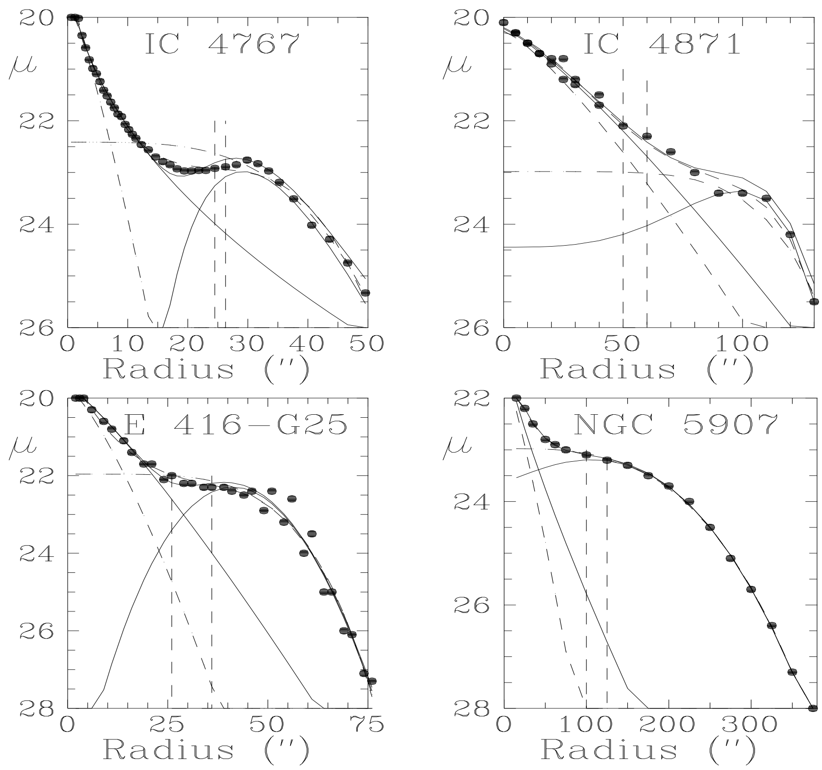

Figure 3: Decompositions of major axis profiles of edge-on galaxies. The solid curves represent the final shapes of the bulge, the disk and the restored profile, obtained by the use of the 2^{nd} order Sersic formula. The dashed curves represent the whole profile, modeled previously by means of 3^{rd} order Sersic formula, as well as the final shapes, obtained by means of the 1^{st} order Sersic formula. The vertical dashed lines show the last used point for the bulge model and the first used point for the disk model. The points between the vertical dashed lines are not used in the models of the bulge and the disk.

giant ellipticals. Exponential number $n \approx 1/2$ corresponds to the profiles of the big ellipticals and bulges of the early type spirals. if $n = 1$ (just the Freeman's law) this corresponds to the small ellipticals and the bulges of the late type galaxies, whereas $n = 2$ (just the Gaussian formula) seems correspond to some dwarf ellipticals and some small bulges of the late type galaxies. Examples are shown in Fig. 2 with dashed lines.

The 2^{nd} order Sersic formula has two scale length parameters. It could describe various shapes of the disks with external and internal truncation, i.e. the ring-like disks. Examples are presented in Fig. 2 with solid lines. In principle the 2^{nd} order formula comprehends the possibilities of the formula of Kormendy (1977), where,

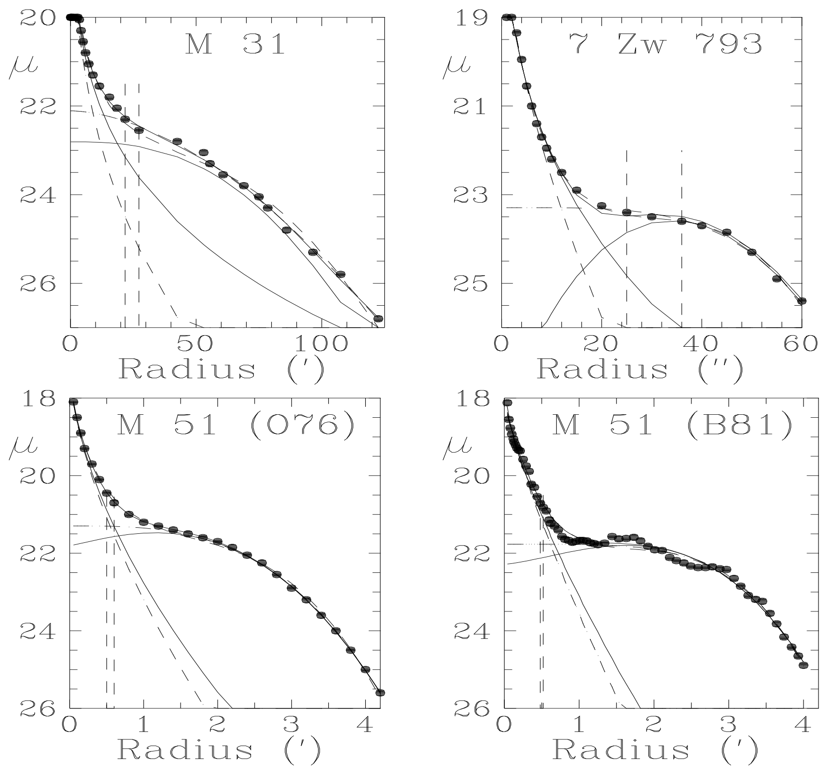

Figure 4: Decompositions of radial profiles of arbitrary oriented nearby galaxies (see the caption under Fig. 3.)

however, the exponential numbers of the first and second terms in Eq. 1. are equal to 1 and 3, respectively, and it describes a disk with exponential outer part and short internal truncation. Examples of the applying of 2^{nd} order formula are given in Figs. 3. and 4.

The 3^{rd} order Sersic formula (Eq. 1.) has three scale length parameters $- h_k = (1.0857/C_k)^{k/n};\ k = 1, 2, 3$. The 3^{rd} order formula occur very useful before decomposition, because its inflex point is the natural dividing point between the bulge and the disk components, which is needed for the automatic beginning of the decomposition. In this case all 4 free parameters in Eq. 1. are derived from the whole observing profile by the MLS, with an application of the nonlinear numerical technique. We note that the inflex point, derived by means of the usual 3^{rd} order MLS polynomial, which is a particular case of Eq. 1. with $n = 1$, lies usually too far from the bulge.

In the present work we show the possibilities of our improved decomposition method for clarifcation of the cases in which the disks have strong central depressions or ring-like shapes. The possible presence of galactic bar is not accounted in this paper.

3. EXAMPLES OF DETECTION OF RING-LIKE DISKS

When a spiral galaxy is oriented edge-on, the integration of the light sources along the line of sight in the disk plane causes amplifying of the curvature of the major axis profile. Our analysis of about 120 published deep profiles shows that this phenomenon is obviously prominent in about 80% of all cases (Stanchev et al., 2002). In the rest cases some problems with the quality and the deepness of the profiles could be suspected. In our previous works we modeled the disk by means of the usual 1^{st} order Sersic formula. We have considered that in some cases this approximation is not sufficiently.

In the present work we show examples with 2^{nd} order formula, which represent the cases with ring-like disks. Examples are given in Figs. 3 and 4.

In Fig. 3 we show the decompositions of the published major axis profiles of 4 edge on galaxies: the "X-like" galaxy with polar ring IC 4767 (Whitemore and Bell, 1988), in B-band), IC 4871 and ESO 416-G25 (Barteldrees and Dettmar, 1994, in R-band), as well as NGC 5907 (van der Kruit and Searle, 1981, in B-band). The disk models, implemented by means of the 1^{st} order Sersic formula (dashed curves), show strong curvatures and almost flat central part. The exponential numbers of the models are 1,2,3,4, respectively. The use of 2^{nd} order Sersic formula (solid curves) underlines the presence of ring-like components. In the first case the profile is a photometry section along the edge-on polar ring of the galaxy IC 4767 and the ring-like shape of the "disk" component is not a surprise. In the second and third cases the edge-on galaxies IC 4871 and ESO 416-G25 show ring-like disks too. In the last example such structure, but not so strongly prominent, is found in the nearby edge-on galaxy NGC 5907.

In Fig. 4 we show the decompositions of the published deep radial profiles in the B-band of 4 galaxies: M 31 (de Vaucouleurs, 1958), 7 Zw 793 (Kormendy, 1977), M 51 (Okamura et al., 1976), M 51 (Boroson, 1981). When the orientation of the galaxy is not edge-on, the ring-like disk structure is less prominent. Though, in the given examples the 1^{st} order formula shows well prominent depressions of the central brightness of the disks (dashed curves) and the 2^{st} order formula elucidates the cases of true ring-like disks. The first example in Fig. 4 is the equivalent profile of the Sb galaxy M 31. The ring-like structures of the gas and the star forming regions of M 31 are well known, but the B-band profile of the disk does not show clearly the ring-like structure. The same result is derived for the B-band profile of M 83 and the Milky Way mass profile (from Freeman, 1970, not shown here). The S0 galaxy 7 Zw 793 in Fig. 4. shows strongly pronounced ring-like disk (see also Kormendy, 1977), well detected by our method. A surprise in the bottom of Fig. 4 is the face-on Sc galaxy M 51 with an active star-forming process. The 1^{st} order formula fits a flat central part of the disk, but the 2^{nd} order formula detects a central depression of about 0.5 mag. This result is derived from two independent photometry data: from Okamura et al. (1976) - equivalent profiles, and from Boroson (1981) - azimutaly averaged profiles of the southern part of the galaxy.

4. CONCLUSION

The application of the 2^{nd} order Sersic formula instead of the 1^{st} order has the advantage to give a flexible model of the disk – smooth and convex. The obvious disadvantage is the increasing of the free parameters, which makes the task of the profile restoration more uncertain. In the present paper we pay attention only on the explanation of ring-like disks and show that the 2^{nd} order Sersic formula is a useful tool for detection of such disks.

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