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The thickness of stellar disks in early-type galaxies

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We suggest and justify a new photometric method allowing the derivation of the relative thickness of a galactic disk from the two-dimensional surface-brightness distribution of the galaxy in the plane of the sky. Key idea of the method is evaluating inclination angle using exponential scalelength distribution in azimuth. We examined calculated inclinations with a sample of 47 nearby disk galaxies with surface-brightness distributions described by exponential law. Images for these galaxies were taken from open archive S4G. The resulting distribution of galaxies on the angles of inclination obtained by our method is satisfactorily uniform. The method of evaluating relative thicknesses was applied to images of 39 early-type (S0Sb) galaxies with known radial exponential or piece-wise-exponential (with a flatter outer profile) surface-brightness distributions. This data was taken from the open SDSS archive. The statistics of the computed relative thicknesses of the stellar disks of early-type galaxies show the following features. The disks of spiral and lenticular early-type galaxies have similar thickness. The presence of a bar yields only a slight increase of the thickness. However, there is a significant difference between the thicknesses of disks with a single exponential brightness profile and exponential disks that represent the inner segments of Type III profiles (after Erwin; i.e., they have an outer exponential disk with a larger scale length). The disks are substantially thicker in the former than in the latter case. This may provide proof that a single exponential scale in a disk surface-brightness distribution forms due to viscosity effects acting over the entire period of star-formation evolution in the disk.

Keywords: Galaxies, galactic disks, galaxies evolution, galaxies structure

1 Introduction

The two primary galaxy structural components – the bulge and the disk – differ in their geometry. Both are spheroids, however the bulges have comparable dimensions across the three axes, whilst the disks are essentially "flat" stellar subsystems with thicknesses being substantially smaller than their radii. Nevertheless the thickness of

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the disks is not negligible, moreover the thickness is often of the same order of magnitude as the radius. The thickness of the stellar disk is an essential parameter for deriving features of dynamical evolution of a galaxy: thicker disk can be an evidence of past "heating" due to gravitational tides or mergers with smaller satellites (Miwa et al. 1998, Walker et al. 1996), while thinner disk could be an evidence of a smooth, laminar accretion of large quantities of cool gas followed by star formation (Reshetnikov, Combes 1997). Observational studies of stellar disk thicknesses up to date have been mainly based on statistics accumulated over large mixed samples of galaxies. Assuming random orientation of the disks in space, the average ratio of the thickness to the radius can be estimated by the distribution of apparent eccentricities for disk projections onto the plane of the sky. The values given by this method vary significantly depending on the sample of galaxies for which the distribution is measured. Latest estimates are $q = 0.21 \pm 0.02$ (Padilla and Strauss 2008) and $q = 0.267 \pm 0.009$ (Rodriguez and Padilla 2013). Measurements of thicknesses for specific disks have so far only been possible when the galaxy is viewed edge-on (Grijs et al. 1996, Mosenkov et al. 2010). Unfortunately, opportunities to make extensive studies based on such galaxies are limited due to the difficulties in decomposition of the galaxy morphology. We propose a new method that allows us to determine thicknesses of specific galaxy disks when the galaxy is viewed almost at any angle except for edge-on or face-on. This enables us to match thicknesses of the disks with the various types of internal structure.

2 Method

We have developed an original method (Chudakova and Sil'chenko 2014) to estimate relative disk thicknesses from the two-dimensional surface-brightness distribution of the disk projected onto the plane of the sky. The method can be applied to galaxies with circular disks with exponential or piecewise-exponential surface brightness profiles. The disks are considered to be plane-parallel, i.e. we assumed that the decline of the volumetric brightness obeys the same exponential law in the equatorial plane and at some distance from this plane, or speaking more formally, $I(R, z) = I_1(R)I_2(z) = I_0 \exp(-R/h)I_2(z)$. In addition it is necessary for the validity of the method that the galaxy be not viewed strictly face-on or strictly edge-on. The key idea of our approach is exploiting the distribution of exponential scale by azimuth. We cut galaxy into sectors and calculate the surface-brightness distribution and exponential scale for each sector. The lines of equal surface brightness (isophotes) and calculated exponential scale for different angles to the major axis of the isophotes provide discrete sets of points separated by equal angles in polar coordinates referenced to the center of the galaxy and its nodal line. Both the isophotes and the exponential scale were fit by ellipses. This approach allows us to estimate separately the oblateness of the isophotes and of the ellipses for the scale coefficients; we find the relative disk thickness by matching these two ellipticities.

2.1 Main formulas

Consider a galaxy with a circular disk with radius a and inclination to the plane of the sky i. Let R be the distance to the center of the galaxy in the plane of the galactic disk, and z be the distance to this plane along rotation axis of the disk. Let us assume that the disk volumetric brightness has an exponential dependence on the radius R and arbitrary dependence on z, expressed by the formula $I(R,z) = I(0)\exp(-R/h)F_q(z)$ (Freeman 1970). Let us compare the brightnesses of points 1 and 2 (Fig. 1) for observations along the z axis ($I(1)$ and $I(2)$) and at some angle to the axis ($I(1)$ and $I(2)$). We assume that the disk thickness function $F_q(z)$ is independent from R and the radial scale h does not depend on z. The surface brightness at a given point of the disk can be obtained by integrating of the volumetric brightness along the line of sight. For the lines of sight corresponding to $I(1)$ and $I(2)$, the volumetric brightness at each point of parallel segments of the lines of sight over which we integrate have the same ratio, $\frac{I(1)}{I(2)} = \exp(\frac{\rho_{12}}{h})$. If F_q is taken to be constant in the radial direction and h to be constant for given galaxy, the proportionality of the volumetric brightnesses holds at each point of the lines of sight corresponding to $I(1)$ and $I(2)$. Therefore, $\frac{I(1')}{I(2')} = \exp(\frac{\rho_{12}}{h})$, too. Thus, the scale h observed along a nodal line does not depend on the inclination of the galactic plane to the line of sight. In the same time, the scale h measured in the plane of the sky at an angle to the nodal line will decrease exclusively due to the effect of projection, showing a cosine dependence on the polar angle. Thus, having constructed an ellipse that fits the distribution of the apparent scale in azimuth in the plane of the sky and measured the eccentricity of this figure

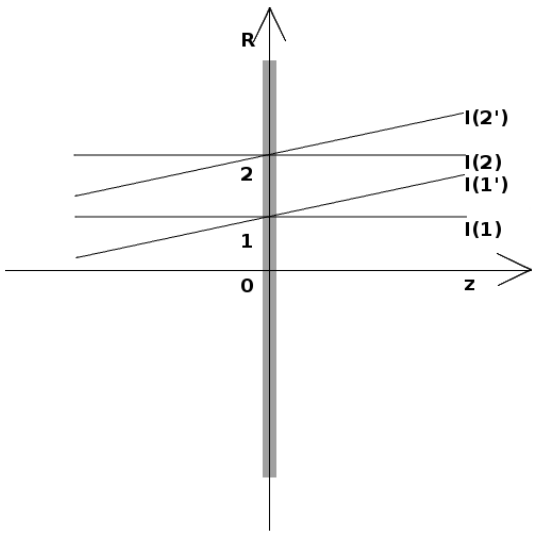


Figure 1 Schematic showing the integration of the disk surface brightness along the line of sight for various disk inclinations to the plane of the sky. The disk is depicted edge-on, and the observers line of sight is in the plane of the sky. Let R be the distance to the galactic center in the plane of the disk, and the axis z be normal to the plane of the disk.

e_h, we can find the inclination of the galactic disk to the plane of the sky i from the following relation:

$$\sin i = \sqrt{2e_h - e_h^2}. \quad (1)$$

It is known (Hubble 1926) that the observed ellipticity of the galaxy image is related to inclination I and measure of oblateness q with the following formula:

$$\sin i = \sqrt{\frac{2e_I - e_I^2}{1 - q^2}}. \quad (2)$$

Thus, inserting (1) into (2), we can obtain the following expression for the thickness of a galactic disk via eccentricities of the isophote and azimuthal distribution of the scale:

$$q = \sqrt{1 - \frac{2e_I - e_I^2}{2e_h - e_h^2}}. \quad (3)$$

2.2 Computation stages

Prior to the computations, the background was filtered from the galaxy image, and stars and bright, compact features such as rings and star formation regions were masked. An approximate isophote $R_n(count)$ can be constructed from the equation $I_n(R_n) = count$ for a given number of counts *count*. An ellipse with eccentricity e_I and semi-major axis a_I fitted to a set of points in polar coordinates, $M_n(count) = (R_n, \frac{\pi n}{10} + \frac{\pi}{20})$, approximates the galaxy isophote at the brightness level *count*. We have split the cleaned galaxy image into sectors. We took the brightest point as the center, and divided the image into 20 non-overlapping sectors with opening angle $\frac{\pi}{10}$ (Fig. 2a). We constructed the surface-brightness distribution $I'_n(\rho)$ for the nth sector – the dependency of the mean brightness I on the distance from the center ρ for the azimuthal angles $\varphi \in \left(\frac{\pi n}{10}; \frac{\pi(n+1)}{10}\right]$ (Fig. 2b). Assuming exponential radial dependency for the disk surface brightness, we computed the scale h_n for each of the 20 sector cross sections. For this purpose, we fitted the set of points $(R_m, 2.5 \log I_n(R_m))$ into the line $1.086(R_m/h) + l$ with linear least squares, where $R_m \in [R_{n0}(j), R_n(count)]$ (Fig. 2c). We selected the R_n0 with the smallest least-squares error for each cross-section. Then, $h_n = h(R_n0)$ is the scale for the nth cross section in the section $[R_n0(count), R_n(count)]$. The set of points in polar coordinates $N_n = (h_n, \frac{\pi n}{10} + \frac{\pi}{20})$ is approximated by an ellipse that corresponds to the scales, with semi-major axis a_h and eccentricity e_h. According to eqs. 1 and 2 we compute the inclination angle i and model relative thickness of the disk (Fig. 2d). For each Type III galaxy, whose full inner surface-brightness profile is approximated by two exponential pieces, we constructed the isophote and ellipse of the scale coefficients separately for each of the two exponential segments. The thickness of the disk was then derived using (3).

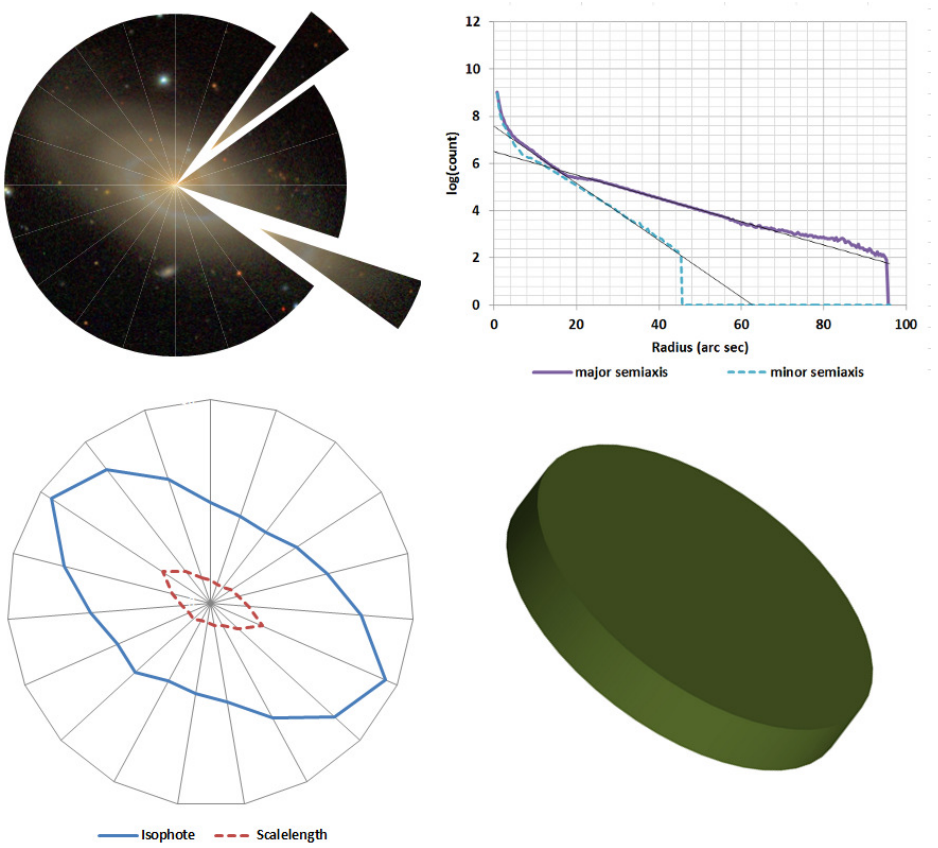


Figure 2 Step-by-step illustration of applying our method on the sample galaxy NGC 5750. Top left: splitting image into sectors. Top right: surface-brightness distributions of 2 sectors with exponential approximation. Bottom left: sets of points approximate isophote (blue) and scalelength azimuthal distribution (red). Bottom right: model relative thickness of disk of galaxy NGC 5750 in our model is 0.33.

3 Galaxy sample and data

To test the method, we compiled two small samples of galaxies with exponential and piecewise-exponential disks, described in (Erwin et al. 2008, Gutiérrez et al. 2011, Mũnos-Mateos et al. 2013). Most of data was taken from the open archives SDSS and S4G. In both samples we are interested in galaxies with single-exponential disks (Type I, Erwin et al. 2008) and with piecewise-exponential disks, with the scale of the outer disk larger than the scale for the inner disk (Type III, Erwin et al. 2008). The first sample containing galaxies of various types is useful for the validation of our method of determining inclination angles. The second sample consists of early-type galaxies and provides us with opportunity to compare distributions of relative thicknesses for some subsamples.

The Spitzer Survey of Stellar Structure in Galaxies (S4G) (Sheth et al. 2010) com-

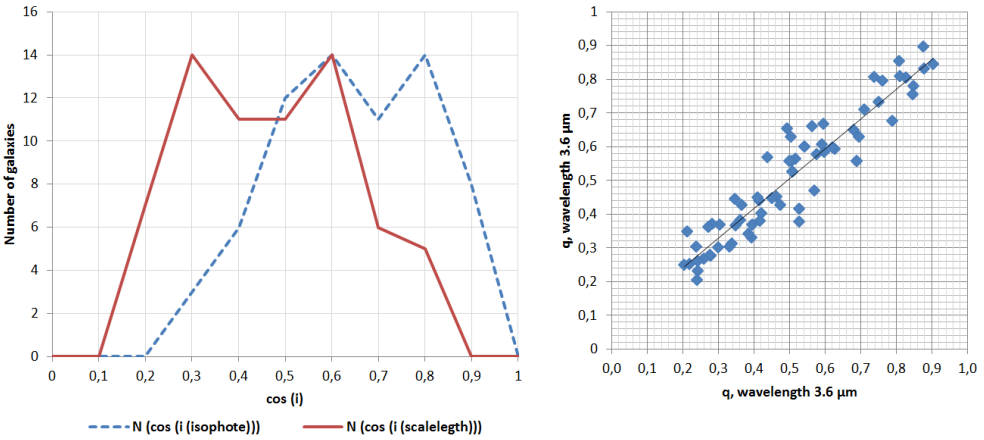


Figure 3 First sample. Left: distribution of galaxies on the cosine of the inclination angle, calculated from isophote (blue) and scalelength (red). Right: correlation between relative thicknesses, calculated from images in wavelength 3.6 μm and 4.5 μm.

prises images of nearby galaxies in wavelength of 3.6 μm and 4.5 μm. Mũnoz-Mateos et al. selected disk-like galaxies and classified decomposition of their surface-brightness distributions. We have chosen pure-exponential (Type I) and anti-truncated piecewise exponential disks (Type III) and looked up their images in S4G archive. Galaxies after successfully applying our method for two images in wavelength 3.6 μm and 4.5 μm made our first sample. So our first sample consists of 47 galaxies of different morphological types. For part of the sample our method allowed us to determine both components of piecewise-exponential disks. As result in the first sample we have 68 different exponential disks, and for each of them there are two sets of computed parameters, calculated from two independent images with different wavelength.

For the second sample, we have taken galaxies described in Erwin et al. (2008), Gutiérrez et al. (2011). For both galaxies with bars described in Erwin et al. (2008) and without bars in Gutiérrez et al. (2011) we left only single-exponential disks (Type I) and anti-truncated disks (Type III). We searched for data for these objects in the photometric survey of the SDSS (Aihara et al. 2011) and added to the sample two common objects with images from the 6-m telescope of the Special Astrophysical Observatory. Also we had to exclude from our sample some images where the method failed. In this way we obtain the second sample of 39 early-type galaxies consists of different types galaxies: spirals and lenticular, Type I and inner disks Type III, with bar and without it.

4 Results

4.1 First sample. Inclination angle

It is known (Masters et al. 2010) that for a full sample of galaxies over morphological types and inclination angles we can observe a uniform distribution of galaxies on the

cosine of the inclination angle in the range $\cos i \in (0.2; 0.6)$. With regards to our first sample we compare these distributions with inclinations calculated by the widely used method using isophote ellipticities and by our method using formula (1). In our sample we have no face-on and edge-on galaxies, and in the range $\cos i \in (0.2; 0.6)$ we expect consistent results. In Fig. 3 we can see that for inclinations calculated using exponential scalelength distribution is approximately constant in the predicted range. For angles calculated from isophotes we can see significant shift of the distribution towards higher cosine values, which suggests underestimation of inclination angles, and it is consistent with our notion that thick disks appear more round. This shift of distributions confirms preference of our method for computing inclination angle.

We have two images in wavelengths of 3.6 μm and 4.5 μm for each galaxy in the first sample. It allows us to compare relative thicknesses, computed from independent images for each galaxy. Figure 3 shows us a good correlation between thickness computed in different wavelength. It proves that our method demonstrates a good stability.

4.2 Second sample. Relative thicknesses

In the second sample of early-type galaxies the accuracy of the SDSS data was satisfactory to derive the thickness of both the inner and outer disks for only two Type III galaxies: NGC 4612 and NGC 4699. The brightness profiles in the cross sections of the major axes of the inner disks of these galaxies are shown on Fig. 4. The arrow marks the isophotal radius at the level $\mu_r = 23.5$, which is the surface brightness count at which we proposed to draw the reference isophotes. The outer disk in NGC 4612 is probably the main (Freeman) disk, while the outer disk in NGC 4699 is located beyond the formal optical boundary of the galaxy and has low surface brightness. Outside this sample we know less than 10 early-type anti-truncated

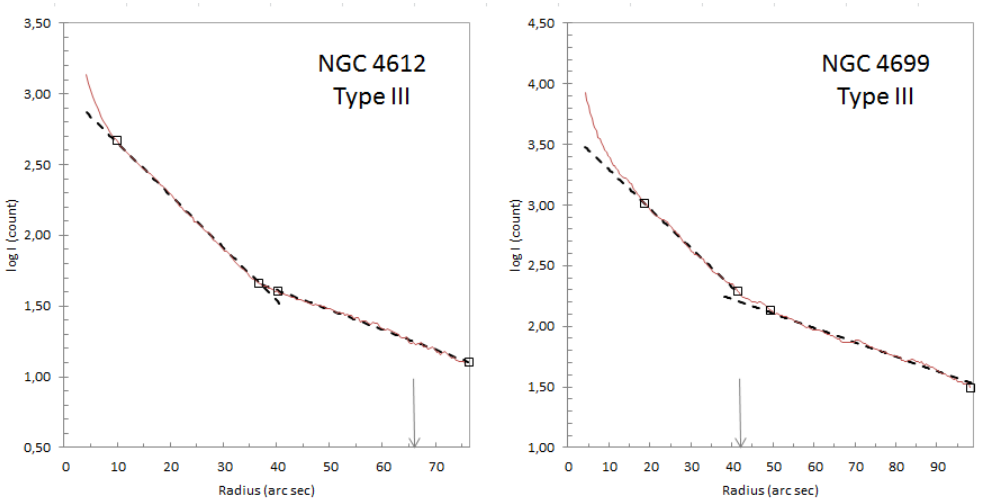


Figure 4 Second sample. Piecewise-exponential surface-brightness profiles of the Type III galaxies NGC 4612 and NGC 4699 in the SDSS r filter.

galaxies with deep enough images for calculating relative thicknesses of both parts of piece-exponential disk. Despite the lack of statistics, in all our samples the outer-disk parameters are surprisingly close: the outer disks are thick ($q = 0.45$–0.65), and much thicker than the inner disks ($q = 0.15$–0.30).

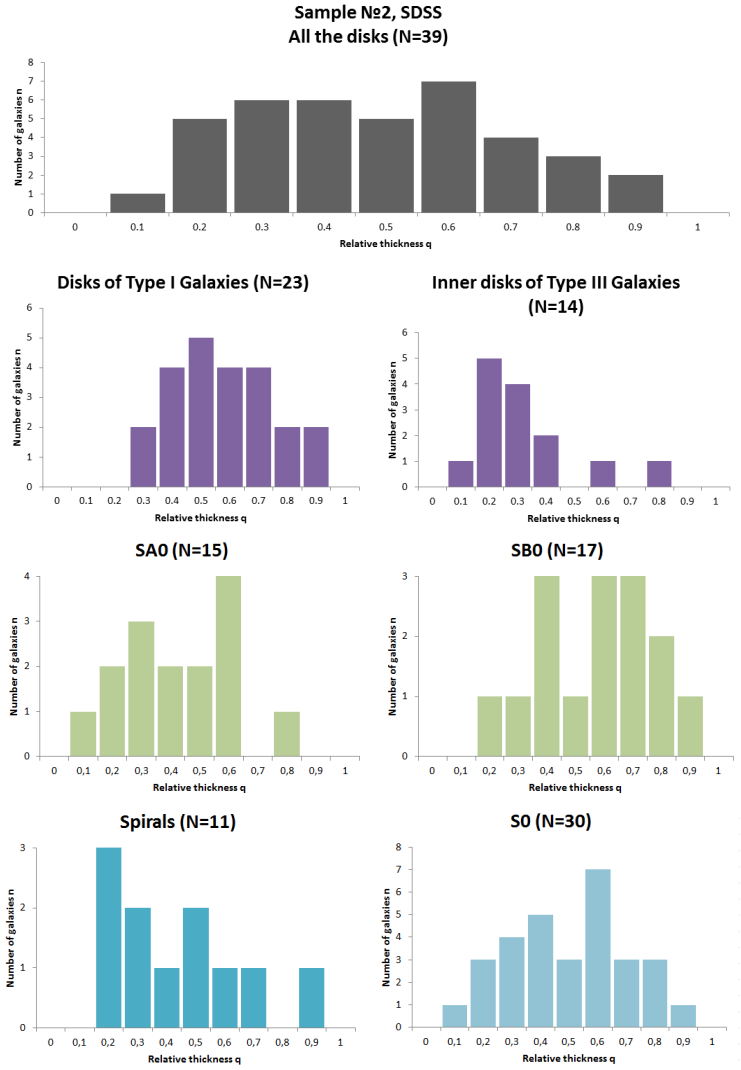


Figure 5 Second sample. First: distributions of the relative thicknesses q of all the stellar disks analyzed. Second: comparison of the distributions of the relative disk thicknesses in the Type I galaxies (single-exponential disks) and the inner disks of the Type III galaxies (two-tiered piecewise-exponential disks). Third: comparison of the distributions of the relative disk thicknesses in lenticular galaxies with (SB0) and without (SA0) bars. Fourth: comparison of distributions of the relative disk thicknesses in lenticular and spiral (Sa–Sb) galaxies.

The following figures show us distributions of relative thicknesses of galaxies in the first sample and some interesting subsamples. In the histogram for the complete sample (Fig. 5) we can see that the mean disk thickness is about 0.38. The histogram for the total sample is very wide, with relative thicknesses ranging from 0 to 0.9. The main result of splitting early-type galaxies to subsamples is presented in the figure. We can see that breaking down the sample according to the type of disk considerably changes the picture. The figure shows that inner-disk thickness for the Type III galaxies (mean thickness 0.19) are statistically significantly thinner than overall disk thickness for the Type I galaxies (mean thickness of 0.48); this conclusion can also be verified with Kolmogorov–Smirnov test. On the remaining histograms we can see no significant difference between subsamples. A Kolmogorov–Smirnov test confirms that splitting sample of early-type galaxies into subsamples based on the presence of bar or morphological type (lenticular vs spiral) does not give significant difference in distribution of relative thickness.

5 Conclusions

We have invented a new method which allows us to determine thicknesses of exponential profile stellar galactic disks seen at arbitrary view angle by analyzing their two-dimensional images. The method is based on the calculation of the true inclinations of the galactic symmetry planes to the line of sight by inspecting azimuthal variations of the projected exponential scalelength. We have tested our method by applying it to some samples of disk galaxies images of which in the optical bands (SDSS) or in the near-infrared (S4G) are available in public databases and are already analyzed in the literature with reference to their in-plane structures. We have confirmed that our method works and gives reliable galaxy inclinations. The preliminary results on the small samples of galaxies with purely exponential disks and with so called antitruncated disks (two-tiered exponential profiles with the more shallow outer parts) have shown that purely exponential disks with a single scalelength over the full galaxy extention are much thicker than the inner disks of the antitruncated galaxies. It may imply strong secular dynamical evolution of galactic stellar-gaseous disks resulting in particular exponential density profiles.

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