A THICKNESS OF STELLAR DISKS OF EDGE-ON GALAXIES AND POSITION OF THEIR TRUNCATION RADII

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Abstract. The relationship between the geometrical properties of stellar disks (a flatness and truncation radius) and the disk kinematics are considered for edge-on galaxies. It is shown that the observed thickness of the disks and the approximate constancy of their thickness along the radius well agrees with the condition of their marginal local gravitational stability. As a consequence, those galaxies whose disks are thinner should harbor more massive dark haloes. The correlation between the de-projected central brightness of the disks and their flatness is found (the low surface brightness disks tend to be the thinnest ones). We also show that positions of observed photometrically determined truncation radii \( R_{\text{cut}} \) for the stellar disks support the idea of marginal local gravitational stability of gaseous protodisks at \( R = R_{\text{cut}} \), and hence the steepening of photometric profiles may be a result of too inefficient star formation beyond \( R_{\text{cut}} \).

1 Introduction

Stellar disks in spiral galaxies consist mainly of old stars and usually include the main part of their stellar content. Being collisionless, they nevertheless may experience the evolution of mass distribution - both along the radial and vertical coordinates due to internal dynamical processes and outer interactions with neighbour systems. What determines the relative disk thickness and disk radial extension, remains an open question. Are these parameters a result of a long lasting evolution or a product of the very early period of the stellar disks formation? The analysis of connection between these parameters and the kinematic properties of galaxies helps to find an answer.

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2 A thickness of stellar disks of edge-on galaxies

A flatness of stellar disks differ strongly from one galaxy to another. As it was found by some authors, photometric axes ratios for flat edge-on galaxies correlate with their morphological type: disks of late-type galaxies (Sc–Sd) are on average “thinner” than that of early-type objects (Karachentsev et al. [1997], de Grijs [1998], Ma et al. [1997, 1999]. At the same time the data of the Revised Flat Galaxy Catalog (Karachentsev et al., 1999, RFGC hereafter) does not reveal any correlation of axes ratios with the rotation velocity or the luminosity. To illustrate it, in Fig. 1 we compare the $B$-band axes ratio $a/b$ according to the catalog RFGC with the known HI line width ($W_{50}$) and with the absolute magnitude $M_B$. Both these parameters were adopted from the LEDA catalog. The relationship between the thickness of the disks and their kinematics, if exists, has to be more sophisticated.

A thickness of a self-gravitating disk depends on its density and the stellar vertical velocity dispersion. It is worth noting that the dynamical heating of a collisionless stellar disk is the one-way process – after the increasing of the stellar velocity dispersion the disk never becomes cooler or thinner again. There are several heating mechanisms known which might increase the vertical scale of the disk, such as a scattering of stars either by massive gas clouds or by other density irregularities, a merging of small satellites, or a gravitational interaction with neighbours. One may easily find the discussion of these mechanisms in the literature. However although the efficiency of any of them should depend on the distance from the galactic center, the observed thickness of disks of edge-on galaxies is usually nearly constant within a wide interval of radial distances.

Fig. 1. The major to minor axis ratio $a/b$ in the $B$-band (according to the RFGC catalog) shows no correlation with the known HI line width ($W_{50}$) and with the absolute magnitude $M_B$. The figure is adopted from Zasov et al. (2002).
Let’s imagine for instance that we have a disk where the initial velocity dispersion of stars in z-direction $C_z$ is very low, say 3 km/s instead of more realistic value 30 km/s. Let also we have neither gas clouds nor satellites or close neighbours. Will a disk stay razor-thin in this case? The answer is definitely NO, and numerical experiments demonstrate it very clearly: the disk always heats up within a short time interval (a couple of rotation periods) as a result of the bending instability which inevitably develops in a thin disk. The thickness ceases to grow when some critical value of $C_z$ is reached. This instability determines the minimum possible thickness for collisionless disks. The other heating processes, if involved, may only increase the vertical scalelength of the disk.

As it is known, the bending instability is in some sense an addition to the classical Jeans instability in the disk plane. Indeed, the increasing of radial velocity dispersion $C_r$ makes the disk more stable to Jeans perturbations and less stable to the bending ones. Hence a growth of $C_r$ leads to the parallel increasing of the vertical dispersion $C_z$. As a result, one can expect the proportionality between $C_r$ and $C_z$ in the final stable state (although, as N-body simulations show, their ratio may depends on the relative masses of spherical and flat components, see Mikhailova et al., 2001). The simplified model of the disk leads to the ratio $C_z/C_r \approx 0.4$ (Polyachenko & Shukhman 1977), whereas the observations of real galaxies inferred the values 0.5 - 0.8 with rather large uncertainties. On the other hand, the minimal value of $C_r$ is determined by the local gravitational stability of the disk. In general case the critical value of $C_r$ is proportional to the surface density over the epicyclic frequency ratio $\Sigma_{disk}/\kappa$. The latter in turn is a function of circular velocity $V(R)$, which makes the minimum possible thickness of the disk connected with the kinematic properties of a galaxy.

Let us use the simple proportions written for some fixed dimensionless radius $R/h$ of a galaxy where $h$ is its radial scalelength:
- the vertical velocity dispersion $C_z \sim C_r$;
- the vertical scalelength $Z_0 \sim C_z^2/\Sigma_{disk}$;
- the minimal radial velocity dispersion $C_r \sim \Sigma_{disk}/\kappa$;
- the total disk mass of a galaxy $M_d \sim \Sigma_{disk}h^2$;
- the total disk mass of a galaxy $M_t \sim V^2h$, and
- the epicyclic frequency $\kappa \sim V/h$.

Combining these expressions, one can find that the minimal relative thickness $Z_0/h$ is expected to be proportional to the relative mass of the disk: $Z_0/h \sim M_d/M_t$.

This conclusion agrees well with the results of the 3D N-body numerical simulations of collisionless initially thin disks embedded into a rigid halo (see Zasov & Morozov 1985, Zasov et al. 1991, Mikhailova et al. 2001, Zasov et al. 2002). Fig. 2 shows the diagram taken from Mikhailova et al. (2001), where the mass ratio of spherical and disk components $M_s/M_d$ is compared with the vertical over radial scalelengths ratio. In accordance with the expectations, the model galaxies with the most massive halo own the thinnest stable disks. The question is whether the real galaxies obey this rule as well.

To verify it, we composed and analysed two samples of edge-on galaxies with
available rotation curves and a surface photometry (see Zasov et al. 2003 for details). All galaxies were taken from RFGC and thought to be disk-dominated objects with a small, if any, bulge contribution to the integrated luminosity. The nearby galaxies, the Virgo cluster members, and galaxies with asymmetric or distorted isophotes were excluded from the consideration.

The first sample includes the objects for which the R-band surface CCD photometry was performed with the 6m telescope at the Special Astrophysical Observatory of RAS (Karachentsev et al. 1992). We estimated the radial scale length $h$ by fitting the photometric major-axis profiles to the analytical expression ob-
Fig. 3. Relation between the photometrically determined radial to vertical disk scale length ratio and the quantity $W_{50}^2 h/GL_{R,K}$, which estimates the total mass-to-luminosity ratio $M/L$ within $R = 4h$: a) for the R-band (the BTA sample); b) for the $K_s$-band (the 2MASS sample).

The comparison of two samples has revealed that the galaxies in the $K_s$-band look systematically thinner than those in the bluer one (in accordance with the results obtained by de Grijs, 1998), and hence, the samples should be considered separately.

The starting point for our comparison of the disk thickness with the relative mass of halo in galaxies is that the presence of a dark halo always increases the total mass-to-luminosity ratio $M/L$ of a galaxy. For definiteness we will estimate all masses within four disk scalelengths $4h$, which encompasses practically all stellar mass and luminosity of the galaxy. In the first approximation the total mass of the galaxy is $M(4h) = W_{50}^2 h/G$. The luminosity was estimated from the photometric parameters of the disks found after the data processing. The diagrams $M/L$ (that is $W_{50}^2 h/GL$) versus $h/Z_0$ are shown in Fig. 3a,b.

One can see that, although the dispersion is rather high, the stellar disks indeed tend to be thicker when $M/L$ is lower. It is better seen for the 2MASS sample, evidently due to the more reliable photometric models and low internal absorption.
Fig. 4. The same diagram as in Fig. 3b with superposed curves, obtained from the numerical simulations (the curve in Fig. 2, recalculated for three adopted values of disk mass-to-luminosity ratios: \((M/L)_{\text{disk}} = 1, 2\) and 3 solar units.

in the infrared band. The existence of this dependence is what we expect if the bending instability is the major factor determining the disk thickness.

Fig. 4 is the same as Fig. 3b with three curves superposed. These curves are what we expect from the N-body numerical simulations for the initially unstable collisionless galactic disks. The prototype of the curves is the model curve shown in Fig. 2 above. It was recalculated to jump from \(M_d/M_s\) to the total ratio \(M/L_{K_s} = W_0^2 h/GL_{K_s}\) using the values \((M/L)_{\text{disk}} = 1, 2\) and 3 solar units for a stellar disk.

One can see that the sample galaxies are actually situated in the domain between \((M/L)_{K_s,\text{disk}} = 1\) and 3 which is quite reasonable for old stellar systems. It indicates that the numerical models of marginally stable disks agree well with observations. In turn, it means that for most of the galaxies the mechanisms of additional disk heating along Z-axis (other than the bending instability) may have a little effect on the vertical disk structure. In this case the approximately constant disk thickness along the radius is just a result of two opposite tendencies:
the radial decreasing of both the surface disk density and the vertical velocity dispersion. The influence of these factors on the vertical scale length cancels each other almost exactly within the extended range of radial distances.

Fig. 5 compares the relative disk thickness and the face-on central surface brightness (the latter was reduced to face-on orientation using the model parameters found from the \( R \)- and the \( K_s \)-band surface brightness distributions). The correlation between these parameters is even more conspicuous than that between \( Z_0/h \) and \( M/L \) in Fig 3a,b. Note that the existence of such a relation is nothing unexpected if to take into account that the "normal" and the low surface brightness galaxies were already shown to exhibit the close relation between \( S_0 \) and the integrated \( M/L \), which characterizes the dark halo mass fraction (see discussion in MacGaugh & de Block 1998). The lower is the central surface brightness (and, consequently, the surface density), the higher is its flatness and hence the dark halo mass fraction in a galaxy (the latter dependence between the brightness and dark halo mass was also discussed by MacGaugh & de Block 1998).

3 Where do the old stellar disks end?

The connection between the radial extent of old stellar disks and their kinematic properties is not so evident as in the case of their thickness. It is well known that many late type galaxies experience the significant steepening of the photometric profiles at some radius (truncation radius) \( R_{cut} \) (usually between 2.5 and 5 of photometric scalelengths \( h \)). As in the case of the disk flattening, the truncation of the disk can be studied most accurately in edge-on galaxies. The nature of
the disk truncation is not well known. Here we meet the well known paradox - the less we know about some event, the easier we find its possible interpretations. Some authors consider the disk truncation as a result of a gas density threshold, beyond which the thermal instability, being responsible for the formation of gas cold phase, is absent. The others tie the observed edge of a disk with condition of the local gravitational instability of gaseous layer (see the references in Pohlen et al. 2000, Bizyaev & Zasov 2002). The scarcity of the data makes it difficult to verify the different scenarios. Both approaches mentioned above may explain more or less successfully the radius where the observed present day star formation rate drops down in nearby galaxies. Nevertheless, this radius do not coincide with the truncation radius of an old stellar disk.

It is rather difficult to verify the role of different mechanisms regulating the star formation rate in the past when the presently observed old stellar disk has formed: the velocity dispersion and the density of a gaseous proto-disk, not even saying about the ultraviolet ionizing field, should strongly differ from those we have today. It is possible however to check the fulfilment of the gravitational stability condition for the proto-disks near the truncation radius. For this purpose we used the fact that the critical density of the primeval gaseous disk depends on the same parameters as the observed thickness of the old stellar disk. In other words, we admit that the current stellar vertical velocity dispersion at the truncation radius is equal to (or, in general case, is not higher than) the velocity dispersion of the parent gas. Indeed, the critical surface density of a thin gaseous disk is $\Sigma_{\text{crit}} \approx C_{\text{gas}} \kappa / Q_T \pi G$ and $\Sigma_{\text{disk}} \approx C_{\text{2}}^{\frac{\sqrt{2}}{\pi G}} Z_0 \cdot F(\rho_{\text{halo}})$, where $Q_T$ is the Toomre stability parameter, and $F(\rho_{\text{halo}})$ is the coefficient taking into account the influence of a halo on the disk thickness. To estimate $\Sigma_{\text{crit}}$, we used Polyachenko et al. (1977) criterium which gives $Q_T \approx \sqrt{\frac{3}{\pi}}$ for a flat rotation curve.

We analysed available data for 16 galaxies with the truncation radii and vertical scalelength values taken from van der Kruit & Searle (1981a, 1981b, 1982) (NGC 891, 4013, 4217, 4244, 4565, 5907, 5907), and from Pohlen et al. 2000 (NGC 2424, ESO187-008, 269-015, 319-026, 321-010, 446-018, 446-044, 528-017 and 581-006), and whose rotation curves were found in the literature. The rotation curves were used to evaluate $\Sigma_{\text{disk}}$, $F(\rho_{\text{halo}})$ and $\kappa$ at $R = R_{\text{cut}}$ for the galaxies chosen. It is well known that the rotation curve decomposing, which we used to find $\Sigma_{\text{disk}}$, is ambiguous. Indeed, a comparison of the best fit model with the maximum disk and the minimum disk models (the latter is chosen as the model where $(M/L_{Ks})_{\text{disk}}$ of the disk is not less than 0.5) shows that the typical uncertainties for the disk mass estimates are about 30%.

The calculations of $\Sigma_{\text{disk}}$ and $\Sigma_{\text{crit}}$ showed that their ratio decreases slowly toward the periphery for all galaxies considered, and is close to unit (within a factor of about 1.5) at $R = R_{\text{cut}}$. Their values at $R = R_{\text{cut}}$ are shown in Fig 6. The filled symbols are related to the galaxies studied by van der Kruit & Searle (1981a, 1981b, 1982), whereas the open ones mark the more distant galaxies taken from Pohlen et al. (2000). The cross marks the position of our Galaxy.

Curiously, the mean velocity dispersion of stars at the truncation radius for the galaxies we considered appears to be close to the turbulent gas velocity in the
Fig. 6. (a) $\Sigma_{\text{disk}}$ vs $\Sigma_{\text{crit}}$ relation at the truncation radii $R_{\text{cut}}$ for the galaxies taken from the two different sources (see the text); our Galaxy is marked by the cross.

Present interstellar medium for star forming galaxies: 10–15 km/s, although it varies from one galaxy to another.

A comparison of the values $\Sigma_{\text{disk}}$ and $\Sigma_{\text{crit}}$ enables us to conclude that the observational data well agree with the assumption that the observed disk truncation in late-type galaxies considered here is connected with the disk kinematics. It supports an idea that the sharp decrease of the surface brightness at $R > R_{\text{cut}}$ might be a result of rather inefficient star formation beyond this radius due to the gravitational stability of outer parts of a primeval gaseous disk at the time of intense formation of the first generation stars.

4 Conclusions

The thickness of stellar disks and their radial extension in most of galaxies are rather conservative parameters reflecting the conditions of the initial formation of galactic disks rather than their long-lasting evolution. In this case the observed dependence of the disk thickness on the relative mass of the dark halo may be nat-
urally explained. The low surface brightness galaxies are to be among those which possesses both the thinnest disks and the highest dark-to-luminous mass ratios. Concerning the galactic truncation radii $R_{cut}$, although we cannot prove their direct relation to the local Jeans instability of the primeval gas disk at $R < R_{cut}$, however this assumption demonstrates a good compatibility with the observed properties of the edge-on galaxies.

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