Edge-on disk galaxies

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Chapter 7

The shape of galaxy disks: how the scale height increases with galactocentric distance

Abstract. We present the results of a detailed study of vertical surface brightness profiles of edge-on disk galaxies. Although the exponential disk scale height is constant to first order, we show that for the large majority of our sample galaxies, the scale height increases with distance along the major axis. The effect is strongest for early-type galaxies, where the increase of the scale height can be as much as a factor of 1.5 per scale length, but is almost 0 for the latest-type galaxies. The effect can be understood if early-type disk galaxies have thick disks with both scale lengths and scale heights larger than those of the dominant disk component. Its origin appears to be linked to the processes that have formed the thick disk.

1 Disk vertical scale parameters

The behaviour of the thickness of galaxy disks is of major importance for understanding the evolution of disk galaxies. Since the exponential vertical scale height can be related directly to the vertical velocity dispersion in (isothermal) disks (e.g., Bahcall & Casertano, 1984), we may be able to constrain models that describe the dynamical heating mechanisms of galactic disks by studying this parameter.

Van der Kruit & Searle (1981a,b, 1982) found, for their sample of edge-on spirals, that the vertical scale parameter, $z_0 = 2\,h_z$, is in good approximation independent of position along the major axis. Later studies of NGC 891 (Kylafis & Bahcall, 1987) and NGC 5907 (Barnaby & Thronson, Jr., 1992) have confirmed this result. From two-dimensional modeling of a sample of 10 edge-on spiral and lenticular galaxies, Shaw & Gilmore (1990) found that the radial variation of scale heights is typically within $\pm$ 3% of the derived mean for the main disk component, with no obvious dependence on colour or model type adopted.

1.1 Why should the scale height be constant?

Van der Kruit & Searle (1982), following a suggestion by Fall, pointed out that the scale height would be constant during the secular evolution of a galactic disk if:

- the disk is continuously heated by, e.g., the random acceleration of the disk stars by giant molecular clouds or spiral structure (Spitzer & Schwarzschild, 1951).
- at all times the star formation rate is proportional to the surface number density of the giant molecular clouds.

In this case the radial distribution of both the vertical velocity dispersion and the surface mass density of the luminous matter would be determined by the radial distribution of the giant molecular clouds. Since the vertical velocity dispersion and surface mass density possess similar radial distributions, their ratio has no radial dependence. The scale height also will not exhibit a dependence on radial distance, since it is proportional to this ratio (van der Kruit & Searle, 1981a; van der Kruit, 1988).

However, at present there is no satisfactory explanation as to how disk heating, the rate of which must vary greatly with radius from the observed distribution of molecular clouds in our own and other galaxies, can naturally lead to this result.

Alternatively, the so-called "self regulation" mechanism for galaxy disks was used to explain the constancy of the vertical scale parameter (see Bertin & Lin, 1987). This mechanism, which describes the disk evolution, leads to a more or less constant value for Toomre's (1964) Q parameter as a function of radius. Combined with an exponentially decreasing velocity dispersion, as found in exponential disks, this leads to a constant scale height (Bottema, 1993).

However, on closer inspection the constancy of the scale height seems to lose strength in the (radially) outer parts in a number of galaxies. For our Galaxy, Kent et al. (1991) find indications that the scale height increases linearly with radius from a minimum radius outwards. The improvement over models with a fixed scale height is significant, although not dramatic.

1.2 A statistically complete sample

In order to be able to draw conclusions based on statistical considerations rather than on individual cases we need a large, homogeneous data set, selected in such a way that unwanted selection biases are avoided.

A diameter-limited sample, taken from the Surface Photometry Catalogue of the ESO-Uppsala Galaxies (ESO-LV; Lauberts & Valentijn, 1989) was used.

We selected all non-interacting galaxies for which either the blue angular diameter (at a surface brightness level of $\mu_B = 25$ mag arcsec^{-2}), D_{25}^B, as measured by an automatic ellipse fitting routine, or the original visual diameter, $D_{\rm vis}$, is greater than 2.′2. From $V/V_{\rm max}$ completeness tests (e.g., Davies, 1990) it follows that the ESO-LV is statistically complete down to blue angular diameters, D_{25}^B and $D_{\rm vis}$ combined, of 1.′0 (see also Chapter 2).

To the diameter-limited sample obtained we applied an inclination selection criterion. As van der Kruit & Searle (1981a) showed, for systems having inclinations $i \geq 86°$ the slopes of both the radial and the vertical structures are independent of inclination (see also de Grijs et al., 1997 [Chapter 8]). Therefore we defined our lower inclination limit to be 87°. Inclinations were determined following de Grijs & van der Kruit (1996, Chapter 4).

For the observed sample the mean $V/V_{\rm max}$ value results in 0.502 ± 0.253, so that we conclude that it is at least statistically complete.

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From the total sample of 93 edge-on galaxies we randomly selected 48, which were observed in optical passbands (B, V, R, and I) using both the Danish 1.54m and the Dutch 0.92m telescopes of the European Southern Observatory at La Silla, Chile, from 1993 to 1996. Both telescopes were used in direct imaging mode, at prime focus.

2 Results

We extracted vertical luminosity profiles at a number of positions along the major axes of the sample galaxies. To do so, the galaxies were binned semi-logarithmically, both radially and vertically, to retain an approximately constant overall signal-to-noise ratio in the resulting vertical profiles and to be able to follow the profiles further out.

In the analysis of the individual profiles, we distinguish between the different sides of the galaxy planes, to avoid possible dust contamination in the case of not perfectly edge-on orientations.

Both van der Kruit (1988) and de Grijs & van der Kruit (1996, Chapter 4), have shown that the vertical profiles are more peaked than expected from an isothermal distribution, but less peaked than exponential, probably close to a sech(z) distribution (but see de Grijs et al., 1997 [Chapter 8]). The analysis shows that we can approximate the profile's shape with an exponential distribution at z heights greater than 1.5 scale heights. We fitted the vertical profiles out to 4 scale heights, thereby taking into account the possible presence of underlying thick disk components. Comparison for 24 galaxies with our unpublished K'-band images showed that in this vertical region the contamination of the stellar light by dust extinction can also be considered to be negligible.

We note that the scale height seems to increase with radius along the major axis, depending on galaxy type. As an example, in Fig. 1 we show representative scale height distributions as a function of position along the galaxies' major axes for galaxies representing various types.

We fitted the scale height distribution as a function of position along the major axis for the total range of data points, between 1.5 and 3.5, and between 2.0 and 4.0 I-band scale lengths. The results obtained for the fitting range between 2.0 and 4.0 scale lengths do not differ significantly from the fitting range between 1.5 and 3.5 scale lengths, whereas the scatter increases if we take all data points, including those dominated by the bulge light contribution.

Fig. 2 shows the results for both the B and the I-band data, for the fitting range between 1.5 and 3.5 scale lengths. We see that they do not differ significantly. This means that the effect is intrinsic to the old disk, and not affected by, e.g., dust or a young stellar population. Especially for the earlier-type galaxies in our sample the observed relationship might be due to a non-negligible bulge contribution. To discard this possibility, we varied our radial fitting range. We estimated the bulge influence by applying a two-dimensional bulge-disk decomposition to the data. For this sample, the bulge contribution can be assumed to be negligible (i.e. less than 5% of the total light) outside 1.8 ± 0.3 I-band scale lengths, depending on galaxy type.

To test our method, we applied the same procedure to the data of van der Kruit & Searle (1981b) for the edge-on galaxy NGC 891, and found that the slopes obtained for NGC 891 fall in the same range as our more recent data. NGC 891 is also included in Fig. 2.

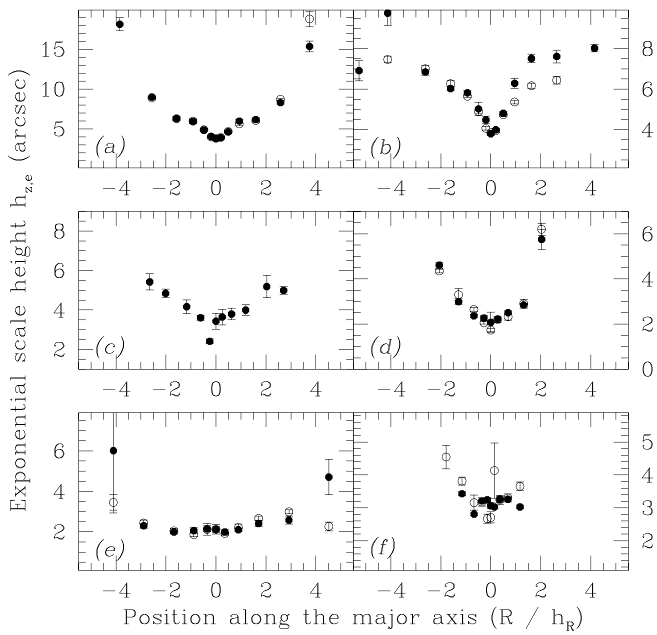

Fig. 1. Examples of the I-band scale height behaviour as a function of galactocentric distance for *(a)* ESO 358-G29 (T = −1.6), *(b)* ESO 311-G12 (T = 0.0), *(c)* ESO 315-G20 (T = 1.0), *(d)* ESO 322-G87 (T = 3.4), *(e)* ESO 435-G50 (T = 5.0), and *(f)* ESO 505-G03 (T = 7.7). Open and closed symbols represent data taken on different sides of the galaxy planes.

To understand better the nature of this effect, in Fig. 3 we show for a few representative galaxies vertical profiles at various radial distances from the centre. In the case of ESO 358-G29 a bright thick disk is seen, with scale length larger than the thin disk. This fact that the scale lengths are different causes the apparent increase of the galaxy's scale height with radius. In the other early-type spirals, except 1, the thick disk cannot be seen so clearly, although the scale height here also increases with radius. We argue that the increase of scale height with radius is linked to the presence of a thick disk, and with galaxy type, since both effects mainly occur in early-type spirals. Based on Fig. 2 it could be that all spirals of type earlier than 2 have a thick disk with scale length larger than the thin disk. To check this we have decomposed all galaxies with type $T < 0.0$ into 2 components with constant scale height. We obtain good fits for all galaxies except for ESO 321-G10, with scale height ratios ranging from 1.8 to 4.6.

3 Discussion

Previous studies have always resulted in confirmations of the assumed constancy of the vertical scale height, although in some cases authors refer to the fact that the outermost profiles in their sample galaxies indicate smaller slopes and hence larger scale heights, e.g., van der Kruit & Searle (1981a) for the late-type edge-on galaxies NGC 4244 and NGC 5907 and de Grijs & van der Kruit (1996, Chapter 4) for a number of their earlier-type sample galaxies.

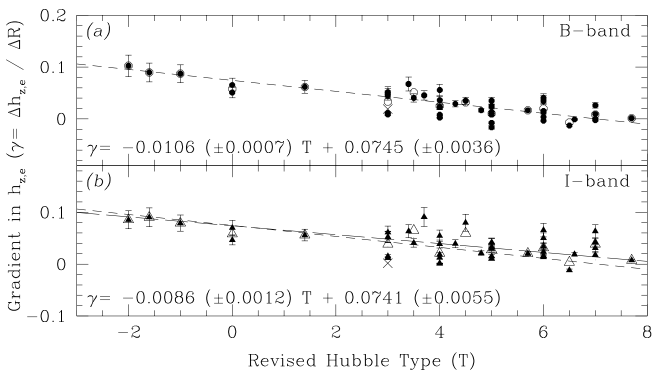

Fig. 2. Disk scale height gradients as a function of revised Hubble type. The closed symbols represent the data; the open symbols are type-averaged data points used to determine the relationship described in the text. The results obtained for NGC 891 are shown as crosses (×). For comparison, the best fit obtained for the *B*-band data is also shown in the *I*-band figure

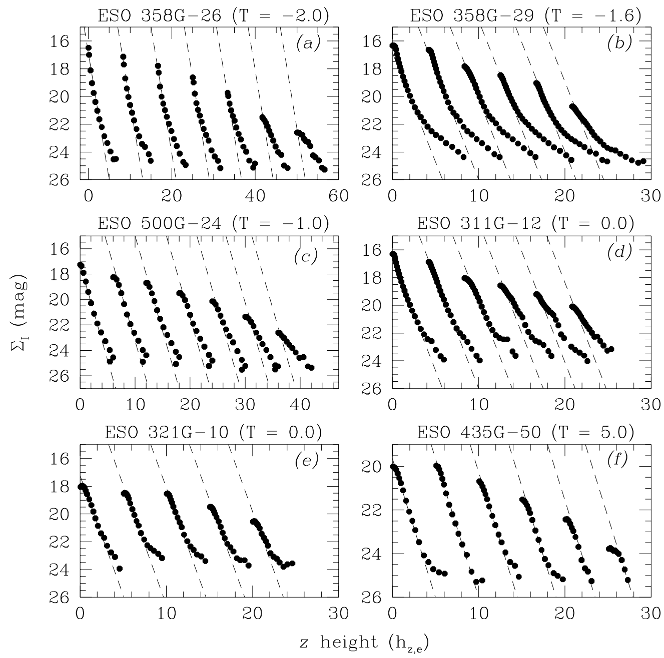

Fig. 3. *(a) – (f)* Examples of increasing scale height with galactocentric distance, compared to fixed scale height models. The fitting of the slopes was done between 1.5 and 4 scale heights. From left to right the profiles that are shown were extracted at logarithmically increasing galactocentric distances

Barnaby & Thronson, Jr. (1992) find for NGC 5907 that the scale height is smaller between $-100''$ and $+100''$ than in the rest of the galaxy. They argue that this is due to bulge contamination. However, as can be seen from their Fig. 4, between $\pm 50''$ and $\pm 100''$ the bulge contribution is negligible.

Van der Kruit & Searle (1981a) explained these observations by invoking a possible thickening of the disk just before the radial cut-off they observed or by attributing it to the influence of an optical warp. However, even if the shallowing at the last profiles were entirely due to a thickening of the disk the implied change in z_0 would be relatively small and restricted to no more than 10% of the observable extent of the galaxies. It should be noted that in a number of profiles their model deviates significantly from the data, although they calculate a single scale height and fit all profiles with a constant vertical scale parameter.

In general, thick disks seem to occur more often in early-type galaxies than in later types (e.g., Burstein, 1979). We have found that the exponential vertical scale height increases as function of position along the major axis and that this dependence is strongest for the earliest-type galaxies. Therefore, it seems a natural theory to link this increase of scale height with radius to the presence of a thick disk.

For that reason, it is likely that the formation mechanism for the thick disk and the origin of the increasing scale height effect are similar. The possibility that the thick disk is the intermediate component in the hierarchical formation scenario between the bulge and the thin disk (as suggested by, e.g., Gilmore, 1984) seems to be ruled out by the large scale length of the thick disk. Therefore, more likely formation mechanisms for the thick disk invoke the accretion of material by the early thin disk, causing violent dynamical heating processes to take place, thereby puffing up the thin disk (e.g., Norris, 1987; Statler, 1989).

Quinn et al. (1993) find that disks following accretions are noticeably flared. The projected and deprojected scale heights of both the original disk and of the final system increase with radius. Quinn et al. (1993) have also shown that the disk is heated in all three directions by the simulated merger event and that in the outer regions the radial velocity dispersion is nearly constant, whereas the vertical dispersion rises. Van der Kruit & Freeman (1986) and Bottema (1993) have studied a number of disk galaxies in detail, especially of later type, and found that the velocity dispersions as a function of radius are consistent with a constant Q parameter (Toomre, 1964), i.e., their measurements are consistent with an exponentially decreasing vertical velocity dispersion, under the assumption of a flat rotation curve.

Bertola et al. (1995) and Fisher (1997) find for their samples of early-type disk galaxies that the stellar velocity dispersions may decrease less rapidly than exponentially, along both the major and minor axes. This result is independent of viewing angle and would indicate that the radial and vertical velocity dispersions become more nearly constant with radius.

These results could imply that our observed increasing scale height with galactocentric distance may be related to the stellar velocity dispersion falling more slowly than predicted by the constant Q model. Similarly, a non-exponential behaviour of the stellar velocity dispersion is suggestive of a non-constant disk scale height, or an increasing thick disk contribution to the mass profile.

Based on detailed modeling of the evolution of gaseous protodisks, Burkert & Yoshii (1996) find that the resulting stellar disks flare with decreasing surface density. This would be expected if the stellar system remembers the exponential tail of the initial self-gravitating isothermal disk model. However, in this way the type dependence cannot be explained.

4 Conclusions

- We have found that, although constant in a first order approximation, the exponential vertical scale height increases as a function of position along the major axis. This effect is strongest for early-type disk galaxies, where this increase can be as much as a factor of 1.5 per scale length.
- This effect might be closely related to the presence of thick disks, with a scale length larger than that of the thin disk. The fact that, in this case, the scale length of the thick disk has to be larger than that of the thin disk strengthens the possibility that the thick disks were made by merging of small satellites (see, e.g., Quinn et al., 1993).
- If, as theory predicts, the scale height is closely coupled to the vertical velocity dispersion, one should see a less rapid decline of the vertical velocity dispersion than an exponential decline.

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