

Tidally-triggered disk thickening

II. Results and interpretations

Vladimir Reshetnikov^{1,2} and Franoise Combes²

¹ Astronomical Institute of St. Petersburg State University, 198904 St. Petersburg, Russia

² DEMIRM, Observatoire de Paris, 61 Av. de l'Observatoire, F-75014 Paris, France

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Abstract. We have reported in a previous paper (Paper I) B, V and I band photometric data for a sample of 24 edge-on interacting spiral galaxies, together with a control sample of 7 edge-on isolated galaxies. We discuss here the main result found in this study: the ratio h/z_0 of the radial exponential scalelength h to the constant scaleheight z_0 is about twice smaller for interacting galaxies. This is found to be due both to a thickening of the plane, and to a radial stripping or shrinking of the stellar disk. If we believe that any galaxy experienced a tidal interaction in the past, we must conclude that continuous gas accretion and subsequent star formation can bring back the ratio h/z_0 to higher values, in a time scale of 1 Gyr.

Key words: galaxies: evolution, general, interactions, photometry, peculiar, spiral

1. Introduction

From the seminal work of Toomre & Toomre (1972) we know how sensitive are galaxy disks to tidal interactions, from the formation of tidal tails and bridges up to the complete disruption of initial disks into a merged system, looking as an elliptical. Even non-merging interactions or minor mergers can thicken and destroy a stellar disk, and this has been advanced as an argument against frequent interactions in a galaxy life, or formation of the bulge through minor mergers in spiral galaxies (e.g. Gunn 1987). Although many vestiges of interactions are observed in present-day galaxies (ripples, shells, plumes, Schweizer 1990), it was assumed that these interactions must have occurred early in the galaxy life, before the formation of the disk.

Toth & Ostriker (1992) have used the argument of the fragility of disks to constrain the frequency of merging and the amount of accretion, and draw the implications on cosmological parameters. They claim that the thickness of the Milky Way disk implies that no more than 4% of its mass can have accreted within the last $5 \cdot 10^9$ yrs; moreover they question the currently fashionable theory of structure growth by hierarchical merging,

which would not be supported by the presence of thin galactic disks, cold enough for spiral waves to develop.

Numerical simulations have been performed to check how fragile galactic disks are with respect to interaction and merging (Quinn et al 1993, Walker et al 1995). But the results depend strongly on the gas hydrodynamics and star-formation processes, since the thin disk can be re-formed continuously through gas infall. The gas accreted can, by its dissipative character, settle in a thin plane, and make the stellar disk thinner by its direct gravitational effect, and by the subsequent star formation. Other unknown parameters could influence the results, as the actual efficiency of dynamical friction, the true flattening of the dark matter, etc... Since the question is not completely settled, it is interesting to check observationally the influence of tidal interactions on the thickening of galaxy disks.

In a preliminary study, Reshetnikov et al (1993) have shown that the disks of strongly interacting spirals are 2-3 times thicker as compared with the disks of normal spiral galaxies. But the sample was only made of 6 galaxies and was too small to derive statistically significant results. Here we investigate the efficiency of tidal disk thickening by observing the thickness of planes in a large enough sample of edge-on interacting galaxies, in comparison to a control sample of isolated galaxies. In Paper I, we have presented the observations and general photometric results. In this report, after describing the reduction methods (Sect. 2), we analyse the thickness of the planes, at various radii, show that it remains almost constant in a given galaxy, i.e. stellar disks are not strongly affected by warping and flaring (Sect. 3). Then we study the statistical variations of the ratio h/z_0 of the radial scalelength h to the scaleheight z_0 , and discuss the results in Sect. 4.

2. Observations and data reduction

2.1. Sample and observations

For a statistical study of the influence of galaxy interactions on the z -structure of the disks of involved galaxies, we selected a sample of apparently edge-on spiral galaxies belonging to

strongly interacting systems. Our sample consists of 24 interacting systems containing at least one edge-on galaxy. The sample is relatively complete since we included practically all known interacting systems that are suitable in angular diameter and could be observed during our observational run (see Paper I). All interacting systems (as far as 7 isolated galaxies) were observed at the OHP 1.2 m telescope in the *B*, *V* and *I* passbands. General photometric results of the observations (including isophotal maps of all objects) are presented in Paper I.

2.2. Reduction

We considered photometric cuts (4-6 typically) along minor axes of the sample galaxies at different galactocentric distances. For the galaxies with warped disks the directions of the minor axes were determined locally as a perpendicular to local major axis direction. The positions of the galaxy planes were determined by averaging the vertical profiles and under assumption of symmetrical light distributions with respect to the planes. In general the vertical cuts of interacting galaxies look quite symmetric (especially in the *I* passband). Comparing asymmetry of the averaged profiles of interacting galaxies with asymmetry of the minor axis profiles in our sample of isolated spirals, we concluded that interacting and normal galaxies are distributed approximately in the same range of inclinations with respect to the line of sight. Following Guthrie (1992), we found that our sample isolated galaxies are, on average, within 6° from edge-on orientation and, therefore, concluded that most interacting edge-on galaxies are in the same range also. Let us note also that according to van der Kruit & Searle (1981a) and Barteldrees & Dettmar (1994) moderate (5° - 10°) deviations from edge-on orientation do not significantly change the slope of vertical surface brightness distribution. Moreover, the control sample of edge-on isolated galaxies is also contaminated by not exactly edge-on objects, so this systematic effect is somewhat compensated when both samples – interacting and non-interacting – are compared.

By statistically studying the disk thickness of edge-on interacting galaxies, we did not consider question about best fitting function for each galaxy and fitted all the averaged vertical profiles by standard $sech^2(z/z_0)$ law (van der Kruit & Searle 1981a), where z is the distance from the galaxy plane and z_0 is the scale height. (At large z a comparison between z_0 value and exponential scale height h_z is possible via $z_0 = 2h_z$.) We choose this function in order to have the largest possible comparison sample of normal galaxies with uniformly determined scale heights. We found that galaxies with published z_0 values are predominant in the literature (e.g., van der Kruit & Searle 1981a,b and 1982a,b (vKS); Barteldrees & Dettmar 1994 (BD)). It should be noted also that “ $sech^2$ -distribution” gives quite satisfactory (within 0.1^m) approximation for most of the sample. This can be understood, since this is the distribution of a self-gravitating isothermal layer of stars; and here the stellar component is representing most of the mass (the gas mass is negligible, and the dark halo mass is very small within the optical disk), and there is only small departures from z -isothermality (e.g.

van der Kruit 1988). Close to the plane, the stars are cooler, but the vertical dispersion at worst can be represented by a $sech(z)$ vertical density profile (instead of a $sech^2(z)$, cf Bottema 1993).

We excluded central regions of the galaxies from our study in order to avoid the bulge light contribution to the fitted profiles. After inspection of the radial surface brightness distribution, we considered vertical cuts at radii along the major axis where the bulge influence is negligible. From the other side, in order to have reasonable photometric profiles with amplitude (difference between central surface brightness and faintest level of the cut) larger than 2^m we excluded faint outer regions of the galaxies. We find that our vertical cuts are distributed, on average, between 1 and 2.4 exponential scalelengths h (see below) of the galaxy disks in the *I* passband.

For some of our sample galaxies the seeing is rather bad (larger than $2''$). The seeing effects do not strongly affect the slopes of the surface brightness profiles (see, for instance, Nieto et al. 1990) and cannot noticeably influence our results. To check the size of this effect, we compared scale height values determined from the original images of the galaxies and after Lucy-Richardson restoration (for this we used standard MIDAS routine, the PSFs were constructed from the star images in the corresponding frames). We found that original frames give about 20% systematically larger values of scale heights for the thinnest (in comparison with star images) galaxies. For most of our objects the effect of seeing is insignificant. Therefore, we corrected z_0 values of some flat galaxies (with z_0 about or less $2''$) for this effect (correction of at most 20%).

To study the structure of galaxies in the radial direction, we extracted major axis profiles of all galaxies. Excluding central bulge-dominated regions, we determined exponential scalelengths by fitting outer parts of the profiles. The *B* band radial cuts of our sample interacting galaxies often look peculiar and asymmetric and does not provide reasonable fit. Therefore, we will use the *I* band derived scalelengths in the following discussion (photometric profiles in the *I* filter are significantly smoother and more regular). Let us note also that our exponential fit of the sample galaxies does not show any systematical difference with literature data. For instance, average central surface brightness of the disks in the *B* band ($\mu_0(B) = 21.2 \pm 0.6$) is close to the canonical Freeman’s (1970) value. The mean *B* to *I* scalelength ratio (1.18 ± 0.26) is in good agreement with de Grijs & van der Kruit (1996) (dGvK) value (1.17 ± 0.10).

3. Results

General characteristics of our sample edge-on galaxies are presented in Table 1. The columns of the table are: galaxy name (see Paper I for galaxy identification); morphological type according to NED¹; adopted distance ($H_0 = 75$ km/s/Mpc); corrected for Galactic absorption absolute blue luminosity and colour *B* – *V* of the galaxy (apparent magnitudes and colours of galaxies are

¹ The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

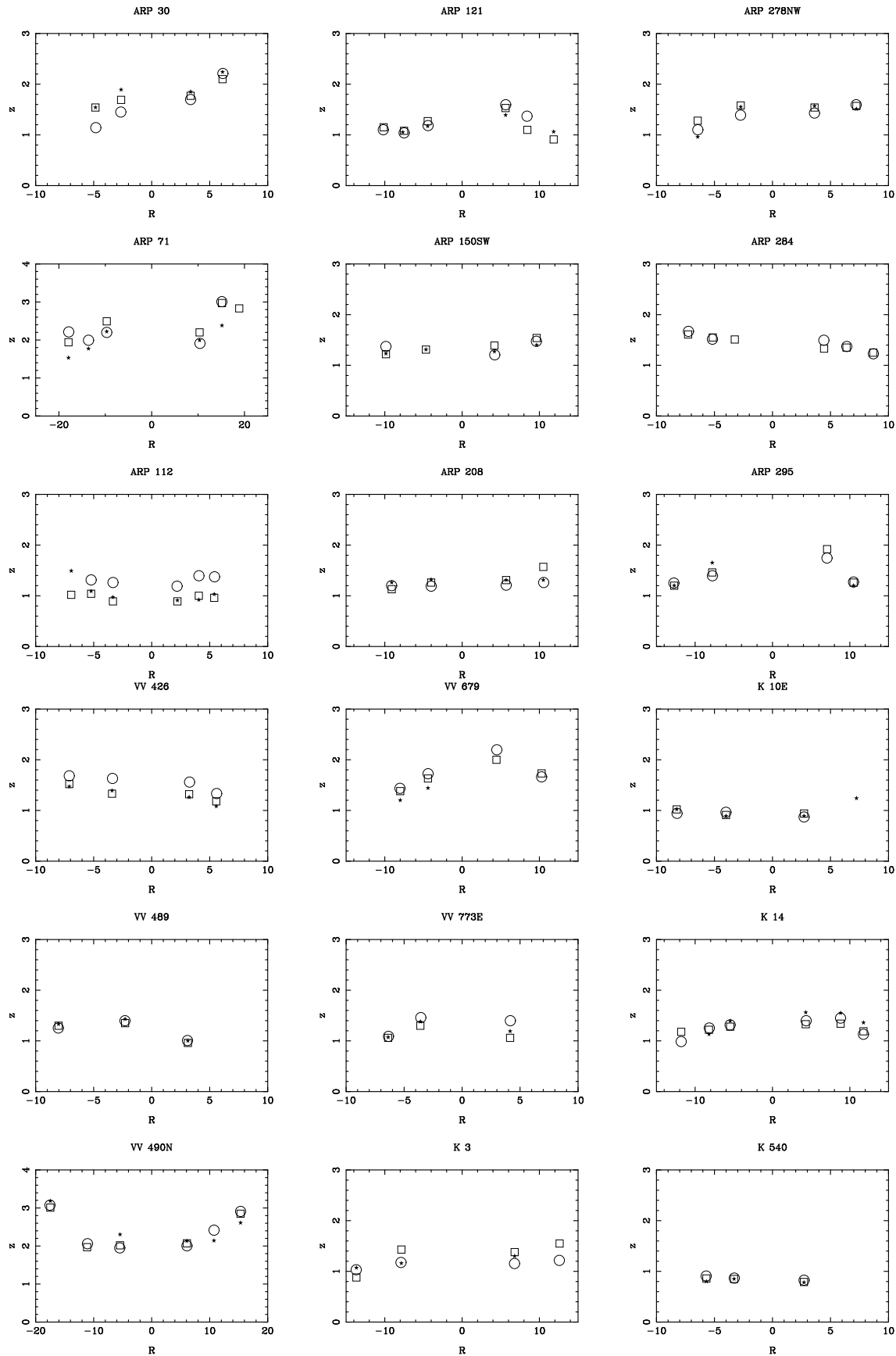


Fig. 1. The scale height distributions for the sample galaxies as a function of radius along the major axis. Both axes are in kpc (in arcsec for Arp 208 and UGC 11230). Circles represent the data in the I passband, squares - V , stars - B . The figures orientations is such that the distance increases from S to N or from E to W. We use general name of interacting system for the systems with one edge-on galaxy and give more detailed name for the objects with less clear identification (see Fig. 1 in PaperI).

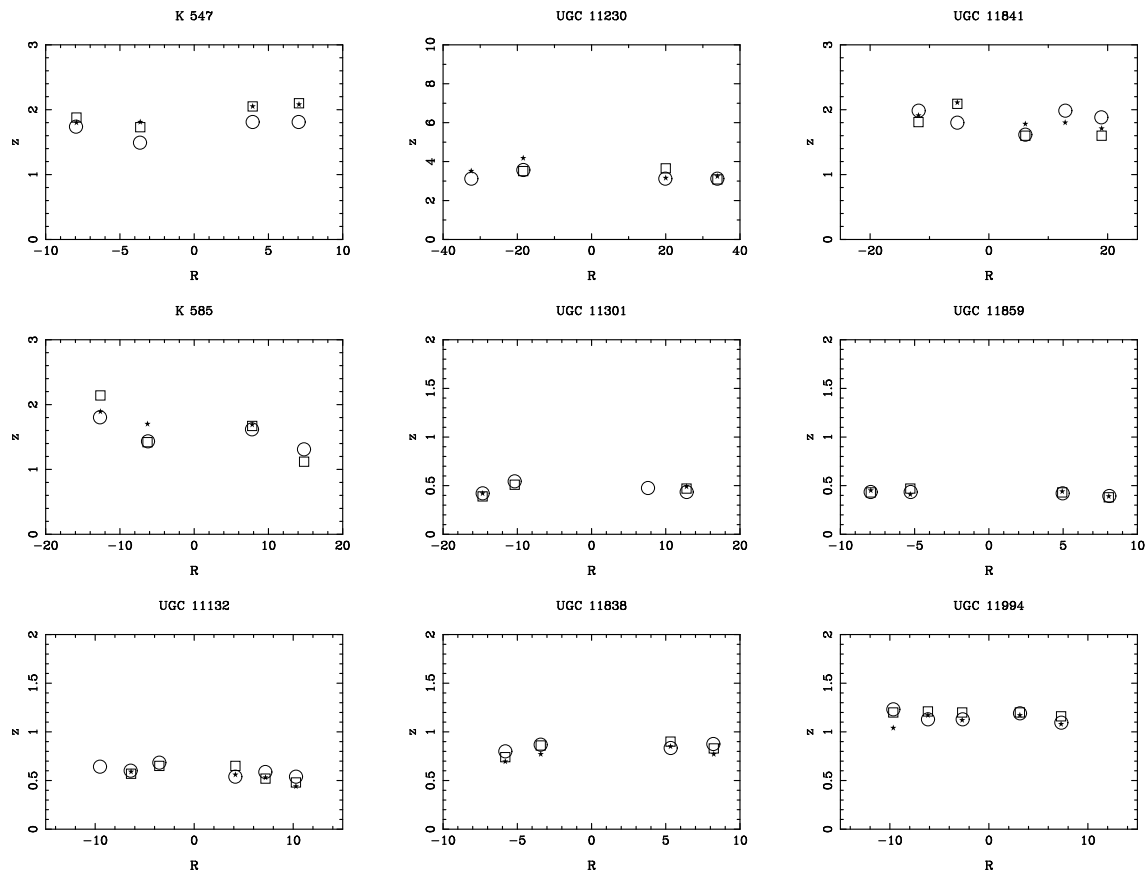


Fig. 1. (continued)

from Paper I); total HI mass, in $10^9 m_{\odot}$, according to Huchtmeier & Richter (1989), de Vaucouleurs et al (1991) (RC3) and LEDA (for the members of Arp 242 we used associated with the central galaxies HI masses according to Hibbard & van Gorkom 1996); HI mass-to-blue luminosity ratio, in m_{\odot}/L_{\odot}^B (adopting $M_{\odot}^B = +5.48$); average scale height in the I passband; scale-length to scale height ratio in the I passband. For two objects - Arp 208 and UGC 11230 - we found no available redshifts and present in Table 1 scale height values in arcseconds.

Two galaxies - Arp 124NE and Arp 127S - are not presented in the table. Arp 124NE demonstrates notable deviation from edge-on orientation (we see dust lane shifted from the galaxy nucleus, photometric profiles along the minor axis look very asymmetric). Arp 127S is embedded in a relatively bright extended envelope which contribute significantly to the observed surface brightness distribution along the minor axis. Moreover, according to NED the components of Arp 127 demonstrate very different radial velocities (Arp 127N - 5065 km/s, Arp 127S - 13650 km/s) so the nature of this double system is unclear.

The distribution of the scale height values in three passbands as a function of position along the major axis is shown in Fig.1 for all sample galaxies with more than two measurements of z_0 .

3.1. Scale heights

3.1.1. Radial distribution of z_0

It is well established that the scale parameter z_0 is almost independent of radial distance for the disks of normal spiral galaxies (vKS, Shaw & Gilmore 1990, dGvK). Our results for seven non-interacting late-type spiral galaxies confirm this conclusion. As one can see in Fig.1, normal spirals demonstrate small variations of scale height with radius. We find that the mean dispersion of z_0 values in the I band is $7\% \pm 3\%$ only (note that this value refer to relatively bright region of the galaxy disk - see item 2.2). This constancy level is consistent with the level of 10-15% found in dGvK.

In agreement with literature data (e.g., Shaw & Gilmore 1990, dGvK), we did not find z_0 variations with passband for our sample isolated spiral galaxies. The mean ratio of scale heights in the I and B passbands is 1.04 ± 0.07 for seven isolated spiral galaxies.

Visual inspection of Fig.1 shows that interacting spirals demonstrate more variety in behaviours than isolated galaxies. The ratio of scale height dispersion to the mean value of z_0 is equal to $11 \pm 6\%$ for them in the I passband. This is almost twice as for non-interacting galaxies. The distribution of $\sigma(z_0)/\langle z_0 \rangle$ values for our sample interacting and isolated galaxies is compared in Fig.2. The distribution for interacting

Table 1. General characteristics of the sample galaxies

Galaxy	Morphological type	Distance (Mpc)	$-M_B$	$(B - V)_0$	m(HI) ($10^9 m_\odot$)	m(HI)/ L_B	$z_0(I)$ (kpc)	$h/z_0(I)$
Arp 30N	dm	113.6	19.89	0.43	3.7	0.26	1.62	2.2
Arp 71A	c	148	20.89	0.90	7.7	0.22	2.40	5.0
Arp 112E		70.4	17.94	0.60	1.9	0.81	1.31	1.4
Arp 121SW	a	76.3	20.40	1.01			1.26	3.4
Arp 150SE		159	21.09	0.89			1.65	2.1
SW	m		20.40	0.77			1.35	3.2
Arp 208W				0.62			1.2''	4.8
Arp 242N		88.7	20.01	0.81	1.1	0.07	2.33	1.8
S	O/a		20.28	0.82	1.3	0.06	2.09:	1.0:
Arp 278NW		67.2	20.26	0.63	11.3	0.57	1.38	4.0
SE			19.80	0.55	6.1	0.47	1.56	2.5
Arp 284E	m	40.1	18.49	0.46	4.7	1.21	1.46	3.2
Arp 286	b	22.7	17.94	0.85	0.76	0.33	0.76	3.3
Arp 295SW	c	94.0	20.24	0.91	10.0	0.52	1.42	2.7
VV 426SE	c	67.2	18.51	0.34	7.6	1.93	1.55	1.3
VV 489S		100.4	20.33	0.52			1.22	3.7
VV 490N	c	97.9	20.35	1.11			2.48	2.3
S			19.28	1.03			1.03	1.3
VV 679A		59.9	19.89	0.54	10.7	0.76	1.75	3.2
VV 773E		74.2	20.77	-0.28			1.31	2.2
W			19.04	-0.09			0.73	3.1
K 3W	c	99.3	18.70	1.00	11.1	2.36	1.14	6.4
K 10E	c	30.3	18.77	0.51	7.7	1.54	1.00	2.3
W			16.80	0.48			0.44	1.6
K 14SW		61.6	19.13	0.88			1.25	4.5
K 540NE		82.2	19.42	0.33			0.87	3.7
K 547E	c	105.5	19.82	0.85			1.71	2.2
K 585	b	79.9	19.29	0.66	18.2	2.25	1.54	3.3
UGC 11132	b	41.0	18.37	0.78	3.5	1.02	0.60	4.2
UGC 11230	c			0.79			3.2''	6.1
UGC 11301	c	62.8	20.58	0.50			0.47	19:
UGC 11838	d	50.1	18.65	0.52	5.75	1.28	0.85	6.5
UGC 11841	cd	83.8	20.09	0.93			1.86	7.2
UGC 11859	c	42.8	17.86	0.75	6.1	2.82	0.45	6.6
UGC 11994	c	68.7	20.13	0.90	12.4	0.71	1.16	3.5

spirals is significantly wider and about half of interacting spirals demonstrate larger scale height variations than it was found for isolated spirals.

The most frequent feature of radial z_0 behaviour of interacting spirals is a systematical change of scale height along the disk (see Fig.1). One can attribute about 40-50% of the galaxies to such “slanting” disks. Probably, “slanting” disk is a transient phase of galaxy evolution caused by large-scale asymmetry of the potential due to proximity of massive companion. Four galaxies (Arp 121, Arp 295, VV 679, and K 14) show an increase of scale height to the central region. Apparently, such disk structure reflects the presence of a bar in the galaxies.

Only one galaxy - VV 490N - demonstrate clearly the radial increase of the disk scale height. Such disk behaviour is expected for the galaxies subject to accretion of small companions (see Fig.1 in Toth & Ostriker 1992, Fig.6 in Quinn et al 1993, Fig.9 in Walker et al 1996). The double system VV 490 resembles remarkably the numerical models studied in those works - it consists of a large spiral galaxy (VV 490N) and a small companion (VV 490S) probably settling to the plane of the primary (Fig.1 in Paper I). The strong flaring of the VV 490N disk begins at $r \approx 2h$ and reaches about 50% at $r \approx 3h$. This is in general quantitative agreement with results of numerical simulations. One can note also that analogous flaring structure

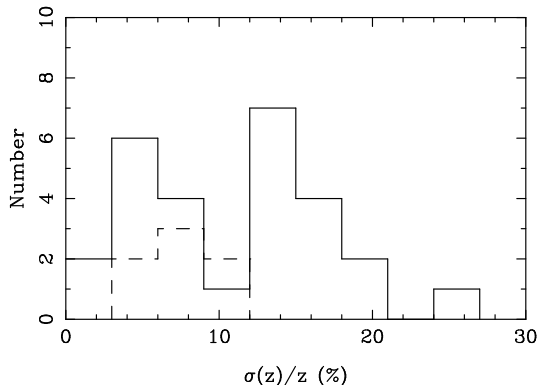


Fig. 2. Distributions of relative variations of scale height for isolated (dashed line) and interacting (solid line) galaxies in the *I* passband.

of stellar disks was found recently in two interacting galaxies - NGC 3808B and NGC 6286 - subject to strong matter accretion from the companions (Reshetnikov et al 1996).

3.1.2. Mean scale heights of interacting and isolated galaxies

The average scale heights in the *I* passband for the sample galaxies are presented in Table 1. As for isolated spirals, we found no colour dependence of z_0 values for interacting galaxies also. The mean ratio of scale heights in the *I* and *B* passbands is 1.00 ± 0.11 for 27 galaxies.

We compare mean values of z_0 for interacting and normal (“field”) galaxies in the Table 2. (Note that according to Karachentsev et al 1993 two non-interacting galaxies in our sample - UGC 11301 and UGC 11841 - are “Malin 1” type galaxies. We excluded them from further consideration.) As one can see, interacting galaxies show larger mean value of z_0 in comparison with our and vKS samples of isolated spirals. The BD sample gives significantly larger average scale height with large dispersion.

The cumulative distribution of scale height values for normal galaxies (we summarized our, vKS and BD samples) is compared with distribution for interacting spirals in Fig.3a,b. Both distributions show the same widths with global peaks at 1.5 kpc for interacting galaxies and about 1 kpc for field spirals. Trying to understand the origin of the secondary peak in Fig.3a at $z_0 \geq 2$ kpc, we inspected normal galaxies falling in this region. Using the DSS² images, we found that among 8 normal galaxies with $z_0 \geq 2$ kpc (7 of them are from the BD sample) at least 6 have comparable size companions within 5 optical diameters. Moreover, several galaxies demonstrate signs of significant non-edge-on orientation. For instance, the most striking galaxy in the BD sample - ESO 460-G31 - with $z_0 = 3.9$ kpc has a companion at one optical radius and notably shifted from the nucleus dust lane. Therefore, the secondary peak at Fig.3a consists of non-isolated galaxies mainly. Normal non-interacting

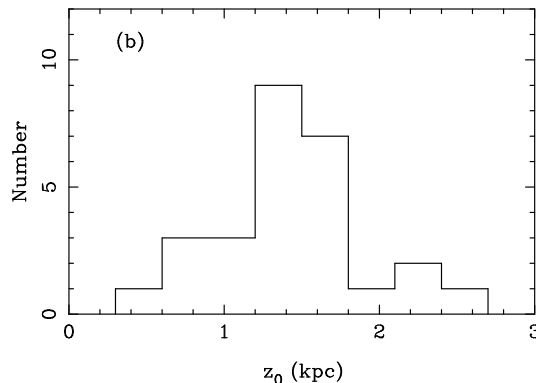
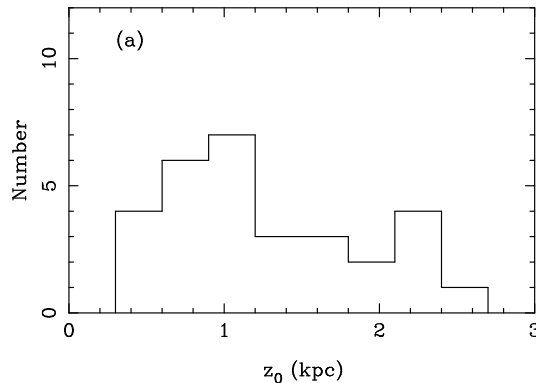


Fig. 3a and b. Distribution of scale heights (in kpc) for normal (a) and interacting (b) galaxies.

galaxies possess disks with scale height about 1 kpc. This conclusion is in agreement with results obtained from the dGvK sample. According to de Grijs & van der Kruit (1996), the exponential scale height of thick disk of spiral galaxies range from about 470 pc to 620 pc. Transforming exponential scale heights to z_0 , we have range 0.94-1.24 kpc that is in good agreement with Fig.3a distribution.

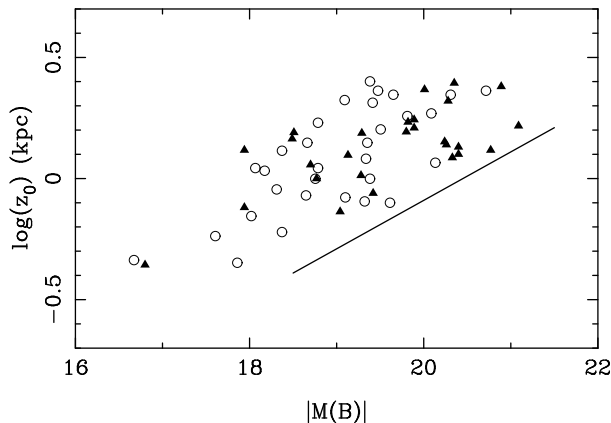
We did not take into consideration possible biases due to different morphological composition and luminosity distribution of the samples of normal and interacting galaxies in our previous analysis. As one can see in Table 1, only half of interacting galaxies have estimated morphological types. Within limits of poor statistics, the distributions of morphological types of our sample edge-on interacting galaxies and normal galaxies in cumulative sample (our+vKS+BD) are undistinguishable. Moreover, both samples do not show statistically significant correlations of scale height on morphological type. From the other side, the absolute luminosity distributions in both samples are close also (for instance, mean absolute blue luminosities of the samples galaxies are -19.1 and -19.6 for normal and interacting galaxies correspondingly with dispersion about 1^m).

In Fig.4 we compare distributions of normal and interacting galaxies in the plane absolute blue luminosity – scale height. As one can see, both samples occupy approximately the same re-

² The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166.

Table 2. Comparison of the samples

Sample	N	$-M_B$	Passband	h (kpc)	z_0 (kpc)	h/z_0
IGs (our)	29	$19.6 \pm 1.0(\sigma)$	I	$4.0 \pm 2.4(\sigma)$	$1.43 \pm 0.49(\sigma)$	$2.9 \pm 1.2(\sigma)$
Field (our)	5	19.3 ± 1.0	I	3.7 ± 1.1	0.77 ± 0.27	5.4 ± 1.3
Field (vKS)	8	18.6 ± 1.0	J	4.5 ± 1.9	1.06 ± 0.51	4.6 ± 1.6
Field (BD)	19	19.2 ± 0.7	g, r	6.6 ± 2.2	1.67 ± 0.76	4.4 ± 1.5
Field (dGvK)	8	18.2 ± 2.0	I	3.25 ± 1.3		5.9 ± 0.4

**Fig. 4.** Distribution of normal (circles) and interacting (solid triangles) edge-on spiral galaxies in the plane absolute blue luminosity – scale height. Solid line represents expected dependence for the “standard” face-on galaxy.

gion in this plane. Solid line in Fig.4 shows $L \propto z_0^2$ dependence expected for normal face-on galaxy with $\mu_0(B) = 21.65$ (Freeman 1970) and $h/z_0 = 5$ (vKS, Bottema 1993). The data for real edge-on galaxies follow this relation quite acceptably with some systematic shift. This shift is a measure of total absorption in the disk of edge-on galaxy in comparison with face-on orientation. Considering only bulgeless galaxies, we find an estimation of total absorption in the B band as 1.6 ± 0.2 mag. This estimation is in remarkable agreement with the RC3 value of 1.5 mag.

Summarizing the results of direct comparison of z_0 distributions for normal and interacting galaxies, one can conclude that there is an evidence of moderately enhanced (at about 50%) disk thickness in interacting spirals.

3.2. h/z_0 ratio

One can expect that normalized thicknesses - h/z_0 ratios - can give more distinct evidence of enhanced thicknesses of interacting disks than absolute values of scale heights. Indeed, as one can see in Table 2, interacting galaxies demonstrate 1.5-2 times

lower mean value of h/z_0 in comparison with all considered samples of normal spirals.

The distribution of h/z_0 ratios for normal galaxies in the joint sample (our+vKS+BD+dGvK) is compared with distribution for interacting spirals in Fig.5a,b. (We neglect in this figure the possible colour dependence of the h/z_0 ratios. But note that exclusion of the vKS data obtained in a relatively blue (close to the B) passband does not change the general shape of distribution for normal galaxies.) As one can see in the figure, both samples demonstrate remarkably different distributions - normal galaxies are peaked at $h/z_0 \approx 4-5$ while interacting spirals show concentration around 2-3. Analysing with the DSS spatial environment of non-interacting galaxies having $h/z_0 \leq 3$ (left wing of distribution in Fig.5a), we found that among 7 such galaxies 5 are non-isolated (see also item 3.1.2). From the other side, among 5 interacting spirals with $h/z_0 \geq 4, 3$ (Arp 208W, K 3W, and K 14SW) demonstrate very regular symmetric optical morphology (see Fig.1 in Paper I) indicative of relatively weak interaction with companions. Exclusion of such contaminated galaxies makes the difference between two distributions in Fig.5 significant at any level of confidence.

In Fig.6 we compare scalelength distributions of normal galaxies in the joint sample and of our interacting spirals. Both distributions are statistically undistinguishable although one can note a somewhat shorter, on average, disks in interacting galaxies. Therefore, taking into account that interacting and normal galaxies demonstrate statistically undistinguishable distributions of morphological types and absolute luminosities also, we can conclude that the difference in h/z_0 ratio must reflect real thickening of interacting disks.

3.3. General observational conclusions

In our analysis of the vertical structure of edge-on interacting galaxies we found that strong tidal influence increases significantly scale height variations along galactic disks even within relatively bright parts of them. The most typical feature of interacting disks is the systematical change of z_0 along the radius.

From the direct comparison of scale height and h/z_0 distributions in the samples of interacting and isolated spirals we found an evidence of moderate (in 1.5-2 times) thickening of galactic disks in interacting systems. This thickening refer to

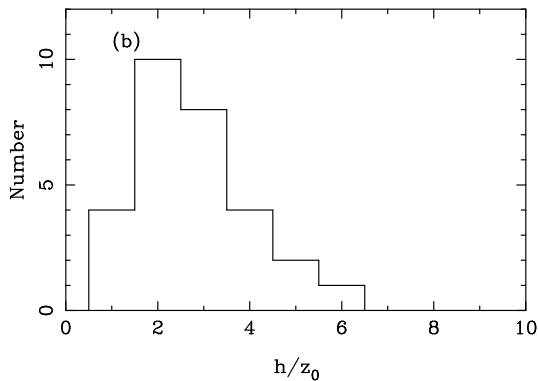
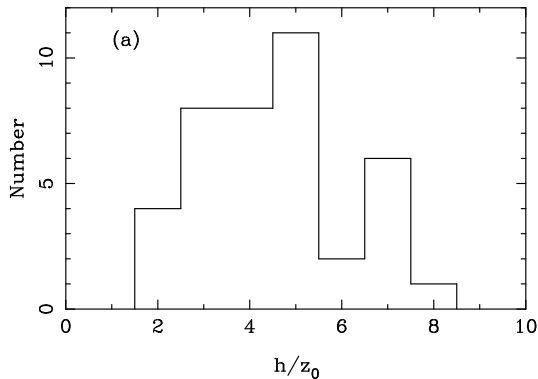


Fig. 5a and b. Distribution of scalelength to scale height ratios for normal (a) and interacting (b) galaxies.

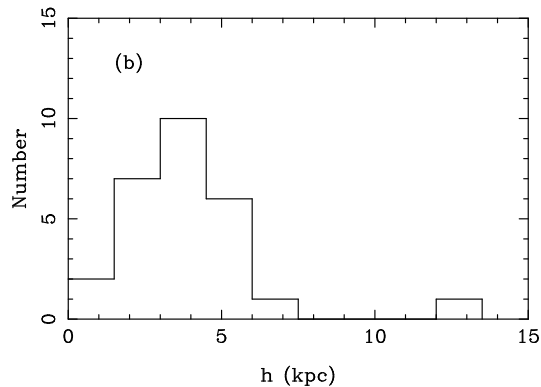
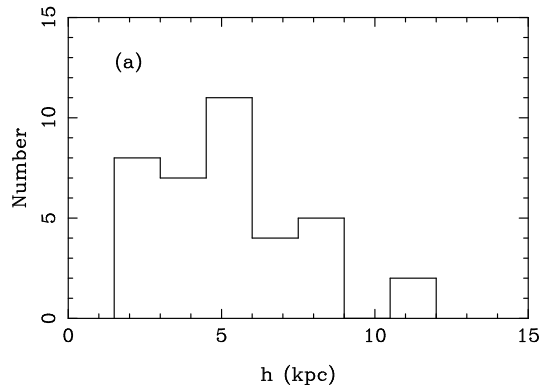


Fig. 6a and b. Distribution of scalelengths (in kpc) for normal (a) and interacting (b) galaxies.

the region of exponential disk between 1 and 2.4 of exponential scalelength (or between 0.6 and 1.4 of effective radius).

The mean characteristics of edge-on interacting galaxies in our sample are: absolute blue luminosity $M_B = -19.6 \pm 1.0$ (so “face-on” magnitude must be about -21), exponential scalelength $h = 4 \pm 2$ kpc. Therefore, typical galaxy in our sample is comparable with the Galaxy and M 31. Most edge-on galaxies have comparable luminosity companions within one optical diameter (see Fig.1 in Paper I). One can conclude from this that tidal interaction between large spiral galaxies like the Milky Way and the Andromeda galaxy at the mutual distance about one optical diameter leads to 1.5-2 times thickening of their stellar disks at half-mass radius of the luminous disk.

4. Discussion

The principal result of our study is that the ratio h/z_0 of the radial scalelength h to the constant scaleheight z_0 is 1.5 to 2 times higher in interacting galaxies than in isolated spiral galaxies. Moreover, the average value found $h/z_0 = 2.9$, is significantly lower than all values found in the literature: Bottema (1993) found that the ratio h/z_0 varies with total galactic luminosity, from 11 for the faintest galaxies to 5.2 for the most luminous, passing through a local minimum of 5.1 for intermediate luminosities. Both h and z_0 increase steadily with luminosity, z_0 by

more than a factor 10. Here we found for the same galaxy types, a much lower ratio h/z_0 , which means that the tidal interaction has a strong effect in relative disk thickening.

First we can note that the effect on the ratio h/z_0 is partly due to the absolute increase of z_0 (cf figure 3), but also to the decrease of h (Fig. 6), so that the effect becomes quite significant on the ratio (Fig. 5). (The tendency for galactic disks to be shorter in strongly interacting systems was mentioned earlier in Reshetnikov et al 1993.) This means that the tidal interaction not only thickens the disk, but also strips its radial extent, or induces a concentration of the stellar disk. This is not unexpected, since it is well known that tidal interaction triggers the transfer of angular momentum outwards, and contributes to the shrinking of the disks and concentration of the mass. This is due to strong non-axisymmetric disturbances generated in the disk by the tidal perturbation, e.g. spirals and bars. Gravity torques then produce mass inflow inside corotation, while some mass is expelled in the outer parts, and take the angular momentum away (Combes 1996). If there is a massive dark halo, it acts as a receiver of angular momentum and helps the visible mass to shrink and condense radially (Barnes 1988).

All these perturbations, thickening of the plane, and radial condensation, leading to a decrease of the ratio h/z_0 , must however be transient, and disappear after the interaction is over, i.e. on a time scale of one Gyr. Indeed, galaxies experience many

interactions in a Hubble time, and those appearing isolated now, must have passed through an interaction period, may be leading to a minor merger. Present galaxies must be the result of merging of some smaller units, according to theories of bottom-up galaxy formation, where small building blocks form first, and large-scale structures virialised subsequently (e.g. Searle & Zinn 1978, Frenk et al 1988). On the observational side, many clues point to the high number of galaxy interactions: existence of shells and ripples in a significant fraction of present early-type galaxies (Schweizer & Seitzer 1988, 1992), number of presently interacting systems extrapolated to earlier times (Toomre 1977). A present day "isolated" galaxy must have experienced at least several interactions in the past, and has probably accreted several tens of percents of its mass in the form of discrete subunits (Ostriker & Tremaine 1975, Schweizer 1990). This implies that the h/z_0 ratio recovers its high average value of 5-11 after the interaction. Since the stellar component alone cannot cool down, this means that the overall reduction of thickness should be due to gas accretion. Spiral galaxies possess HI gas reservoirs in their outer parts, that remain available for star formation. Some of this gas can be driven inwards by gravity torques due to a tidal interaction (Braine & Combes 1993). Through this increase of potential well in the plane, the stellar component can react with a slightly reduced thickness; but the main consequence will be the formation of young stars in a very thin layer. The overall thickness will be reduced, which can explain our statistical results about h/z_0 . The signature of these interacting events are observed at the present time in terms of different stellar components in the vertical distribution of galaxies: the presence of thin and thick disks. In the Milky Way, the existence of the thick disk has been known for a long time: from *in situ* star counts in the direction of the south galactic pole (Gilmore & Reid 1983) and high proper motions star surveys in the solar neighborhood (Sandage & Fouts 1987). The age, metallicity and kinematics of the stars in the thick disk are intermediate between that of the thin disk and halo. From the chemical evolution, it is recognized that a substantial delay must have occurred between the formation of the thick and thin disks (e.g. Pardi et al 1995). Recently, Robin et al (1996) determined the main characteristics of the thick disk population using photometric star counts and a model of population synthesis. They found a true discontinuity between thin and thick disks, with no kinematic or abundance gradient in the thick disk, favoring the merging event hypothesis for the thickening of the disk. They claim a scaleheight of 760 pc for the thick disk, with a scalelength of 2.8 kpc, giving a h/z_0 ratio of 3.7, still too small for a non-interacting galaxy. This might suggest that the interactions with the many dwarfs companions of our Galaxy (Ibata et al 1994) or the Magellanic Clouds have still an action on its thickness. This is even more obvious with the scaleheight parameters adopted by Reid & Majewski (1993), for whom $z_0 = 1.5$ kpc. This view is also in agreement with recent chemical models of the Milky Way. Chiappini et al (1996) show that the recent constraints, including metallicity distribution of G-dwarf stars, impose that the disk of the Galaxy has been built at least in two main infall episodes. The halo and thick disk have formed rapidly (in a time-scale of

1 Gyr), while the thin disk is much slower to form (time-scale 8 Gyr), and the gas forming the thin disk must come from the intergalactic medium (and not from the gas shed by the halo).

As it is evident from the above discussion, one can expect a dependence between galaxy thickness and global content of HI. Fig.7 presents distributions of normal galaxies with known HI mass in the joint sample (our+vKS+BD) and of our sample interacting galaxies in the planes $m(\text{HI})/L_B - z_0$ and h/z_0 (L_B values corrected for Galactic absorption only.). There is good ($r = -0.7$) inverse correlation between the HI content of a normal galaxy and its scale height (Fig.7a). Relative thickness of a galaxy - h/z_0 - also correlates with HI content (Fig.7b). (Also, a related dependence between $(B - V)_0$ colour and galaxy thickness is present but with less confidence.) Dashed lines in figure 7 show double regression fits for normal spirals: $z_0(\text{kpc}) = 0.84 \times [M(\text{HI})/L_B]^{-1/2}$ and $h/z_0 = 5.0 \times [M(\text{HI})/L_B]^{1/2}$, where $M(\text{HI})$ is the total HI mass (in M_\odot) and L_B is the total luminosity of the edge-on galaxy (in L_B^\odot) uncorrected for internal absorption. It is interesting that the Milky Way is also satisfying the above relations. Adopting for the absolute luminosity of "edge-on" Milky Way $M_B \approx -20.5 + 1.5 = -19.0$ and $M(\text{HI}) = 4 \times 10^9 M_\odot$, we obtain from the above correlations $z_0 = 1.0 \pm 0.27$ kpc and $h/z_0 = 4.0 \pm 1.7$. These values are in agreement with current estimates of the Milky Way parameters (e.g. Sackett 1997).

Interacting galaxies in general follow the same relations as normal galaxies but with larger scatter. Existence of this correlation can be attributed to the dissipative character of the gas: after a perturbation event that heats both the stellar and gas disks, the gas can dissipate the extra-kinetic energy away, and flatten again to its regulated thin disk. Regulation is probably due to gravitational instabilities, as developed by Lin & Pringle (1987): instabilities heats the medium until Toomre Q parameter is high enough to suppress gravitational instabilities. The gas then cools down until instabilities enter again the process. This feed-back mechanism could explain why the observed gas velocity dispersion is constant with radius (e.g. Dickey et al 1990). In very gas rich galaxies, after a galaxy interaction that has heated the stellar disk, gas dissipation can quickly makes the galaxy recover its equilibrium thickness, through star formation in the thin gas disk. The mass ratio between the thick and thin stellar disk depends strongly on the gas content, and will determine the final global disk thickness. Note that this correlation is also related to that found by Bottema (1993) as a function of mass. Fainter objects correspond to late-type galaxies which are proportionally more gas-rich, and show the higher h/z_0 ratios.

It is interesting to compare our observational results to the predictions of N-body simulations. Quinn et al (1993) have addressed the specific problem of disk heating by small satellites, through stellar tree-code calculations. They found that the disk heats vertically as well as radially; however the radial spread is accompanied by a central mass concentration and the inner disk scalelength h decreases, while the central brightness increases, and the scaleheight z_0 increases during an interaction. This corresponds quite well to our observations of a lower h/z_0 ratio for interacting galaxies. Quantitatively, they found in average a decrease of h by 20%, while z_0 increases by a factor 2. Their

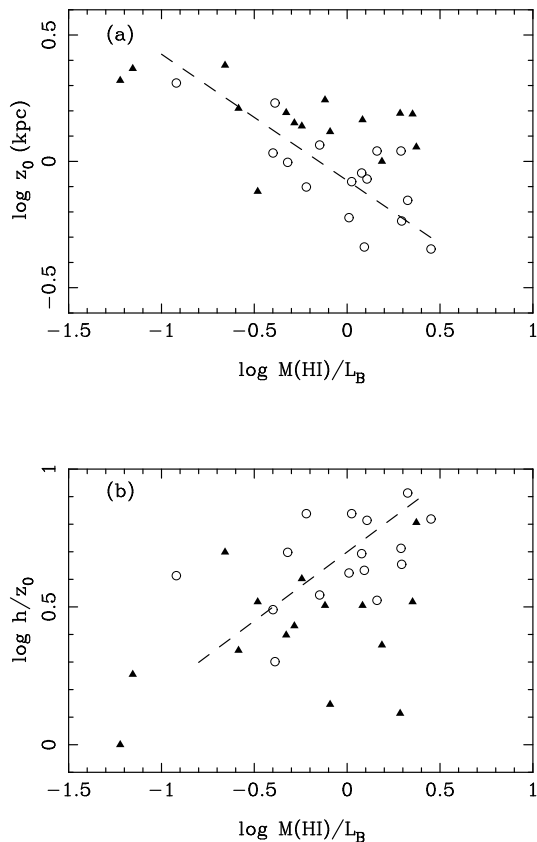


Fig. 7a and b. Distribution of normal (circles) and interacting (solid triangles) galaxies in the plane HI mass-to-blue luminosity ratio – scale height (a) and HI mass-to-blue luminosity ratio – h/z_0 (b).

simulations however over-estimate the disk heating, since their dark matter halo is rigid, and cannot acquire energy and angular momentum, and they ignore the gaseous component, that can dissipate away the energy through radiation. They show that the internal heating of the primary disk depends strongly on the mass concentration of the satellite: when the latter is denser than the primary, it is not disrupted until the final merging, while when the satellite is more diffuse, it is stripped all along the interaction, and the stripped particles can take the heating away. In this case, about 95% of the disk heating must occur in the vertical direction, since the planar kinetic energy resides in the stripped stars of the satellite. Indirect effects can then modify somewhat this picture: if a strong spiral structure is triggered in the disk, this gravitational instability heats the disk, which spreads out as the angular momentum is transferred outwards. The final result depends however on the amount of gas present, and the Quinn et al (1993) simulations did not include it.

Quinn et al (1993) predicted that the final scale height z_0 should increase with radius, i.e. the thickened disk should flare. This is not generally seen in our observations; only the double system VV 490 reveals a strong flare (by 50%); but the phenomenon in the simulations is significant only after 10 kpc in radius, and our observations are not sensitive enough at large radii. Shaw & Gilmore (1989, 1990) also found a constant scale-

height for their sample of isolated undisturbed edge-on galaxies. This does not seem to support the numerical predictions, since long after an interaction, the flaring is expected to subsist in the thick disk. Only in rare cases the stellar disk reveals a flaring (e.g. NGC 3115, Cappacioli et al 1988).

The simulations by Walker et al (1996) improved over the first work by Quinn et al (1993) in treating the dark haloes consistently, and dealing with an order of magnitude more particles. However the results are quite similar, they found a decrease of the scalelength of the inner disk h of about 15%, while the envelope in the outer parts was enriched through radial spreading of the primary disk. The thickness of the disk increased by 60% at the solar distance from the center. This figures imply a disk heating only slightly inferior to what was found by Quinn et al (1993), and completely within the variations expected from the nature of the satellite (dense or diffuse). They also ignored the gas component, which could bring more qualitative differences. Hernquist & Mihos (1995) simulated minor mergers between gas-rich disks and less massive dwarf galaxies. The large difference they found with comparable simulations without gas, is the huge central mass concentration driven by tidal torques due to tidally-induced bars on the gas. Half of the gas mass is driven to a region less than 1 kpc across, and triggers a starburst there. Consequent to the central mass concentration, the inner scalelength of the disk decreases, while the disk thickens. Unfortunately, star-formation was not included in these simulations, which might over-estimate the gas inflow.

5. Conclusions

We have studied a sample of 24 edge-on interacting galaxies and compared them to other edge-on isolated galaxies, to investigate the effects of tidal interaction on disk thickening. We find for most of the galaxies a constant (within 20%) scaleheight with radius. Only one system (VV 490) reveals a significant flaring. The average scaleheight z_0 is higher for the interacting sample, and the scalelength is also smaller, so that the h/z_0 ratio is 1.5-2 times smaller than in isolated galaxies. This corresponds quite well to the predictions of N-body simulations (Quinn et al 1993, Walker et al 1996): the gravity torques induced by the tidal interaction produce a central mass concentration, while the outer disk spreads out radially, leading to a decrease of h . Most of the heating is expected to be vertical, since the planar heating is taken away by the stripped stars either in the primary or in the satellite. The quantitative agreement between observations and simulations is rather good, given the large dispersion expected due to the initial morphology of the interacting galaxies: a dense satellite will produce much more heating than a diffuse one, where stripped stars take the orbital energy away; a mass-condensed primary will inhibit tidally-induced spiral and bar perturbations, that are the source of heating both radially and vertically.

The fact that tidal interactions and minor mergers must have involved every galaxy in a Hubble time, and therefore also the presently isolated and undisturbed galaxies, tells us that the lower values of h/z_0 observed for the interacting sample

must be transient. Radial gas inflow induced by the interaction may have contributed to reform a thin young stellar disk, while the vertical thickening have formed the thick disk components now observed in the Milky Way and many nearby galaxies (e.g. Burstein 1979, Shaw & Gilmore 1989). This process might be occurring all along the interaction, so that the galaxy is never observed without a thin disk. One cannot therefore date back the period of the last interaction by the age of the thin disk, as has been proposed by Toth & Ostriker (1992) and Quinn et al (1993). The Milky Way, experiencing now interactions with the Magellanic Clouds and a few dwarf spheroidal companions, has still a substantial gaseous and stellar thin disk. More self-consistent simulations, including gas and star-formation, must be performed to derive more significant predictions.

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