STRUCTURE AND DYNAMICS OF DISKS IN GALAXIES

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and

KINEMATICS AND DYNAMICS OF THE "SUPERTHIN" EDGE-ON DISK GALAXY IC 5249

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PROPERTIES OF DISKS

The exponential nature of the light distribution in galactic disks was extended with the self-gravitating isothermal sheet description for the vertical distribution (van der Kruit & Searle, 1981):

$$L(R,z) = L(0,0)\,\mathrm{e}^{-R/h_{\mathrm{R}}}\,\mathrm{sech}^2\left(\frac{z}{z_{\circ}}\right).$$

The isothermal assumption was dropped and replaced by the family of models (van der Kruit, 1988)

$$L(R,z) = L(0,0)\,\mathrm{e}^{-R/h_{\mathrm{R}}}\,\mathrm{sech}^{2/n}\left(\frac{nz}{2h_{\mathrm{z}}}\right).$$

This ranges from the isothermal distribution for $n = 1$ to the exponential function for $n = \infty$.

From actual fits to surface photometry in I and K' de Grijs, Peletier & van der Kruit (1997) found

$$\frac{2}{n} = 0.54 \pm 0.20.$$

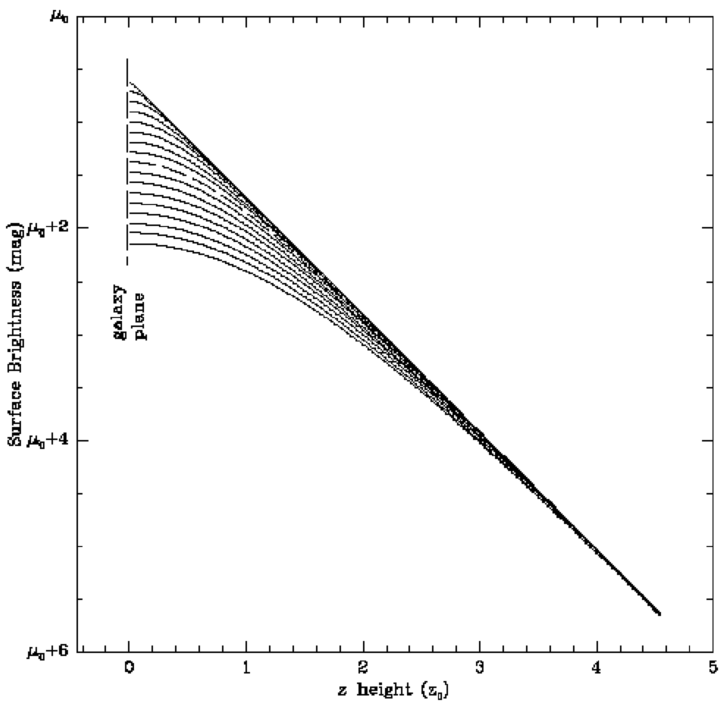
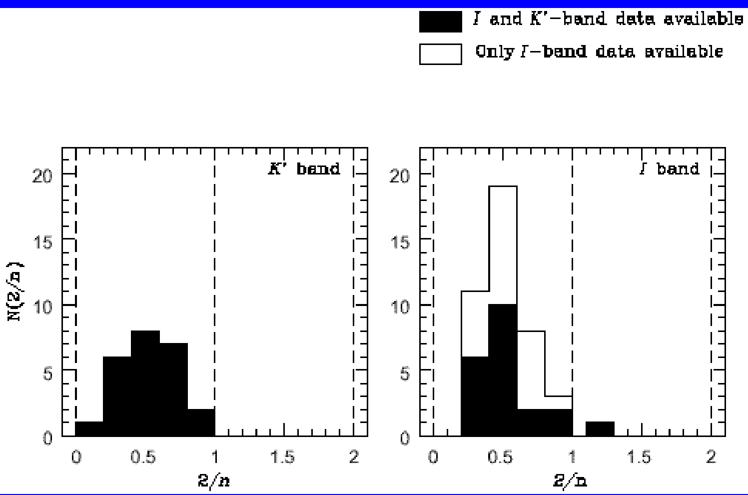


Fig. 4. The family of density (luminosity) laws (6) with the isothermal ($2/n$ = 2.0) and the exponential ($2/n$ = 0.0) distributions as the two extremes. The difference in $2/n$ between two successive model distributions is 0.125; for clarity, the sech(z) model distribution ($2/n$ = 1.0) is shown as the dashed profile (μ_0 is the central surface brightness).



In what follows I will take the whole range from the sech-function to the exponential into account in the coefficients in the equations.

In other words, I will use $n = 2 - \infty$ $(2/n = 0 - 1)$.

Assume a constant mass-to-light ratio M/L, so that the luminosity density $L(R,z)$ can be replaced by the space density $\rho(R,z)$.

Then the surface density becomes

$$\Sigma(R) = (2.6 \pm 0.6)\rho(R,0)h_z,$$

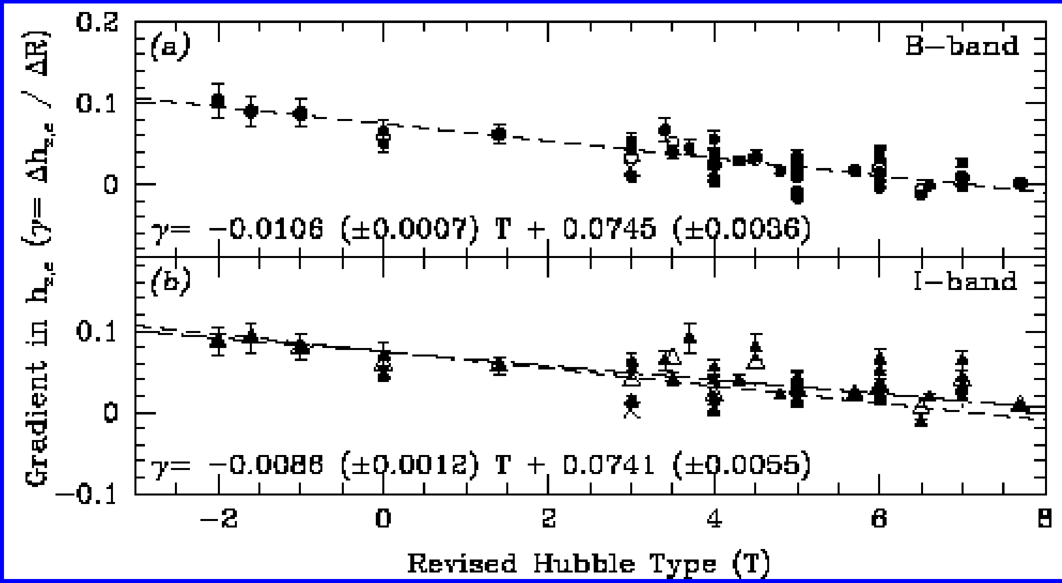
the vertical velocity dispersion in the plane

$$(\sigma_z)_{z=\circ} = \sqrt{(4.0 \pm 0.9)G\Sigma(R)h_z},$$

and the z-velocity dispersion integrated along a line of sight perpendicular to the plane

$$\sigma_z = \sqrt{(5.0 \pm 0.2)G\Sigma(R)h_z}.$$

The vertical scaleheight h_z is constant with radius (at least for late-type galaxies; see de Grijs & Peletier, 1997).



Then we expect

$$\sigma_z^2 \propto e^{-R/2h_R}.$$

This is consistent with observations by van der Kruit & Freeman (1986) and in Roelof Bottema's thesis (1995), at least out to about 2 scalelengths.

Rob Swaters in his thesis (1999) found it in the late-type dwarf UGC 4325, again out to about 2 scalelengths.

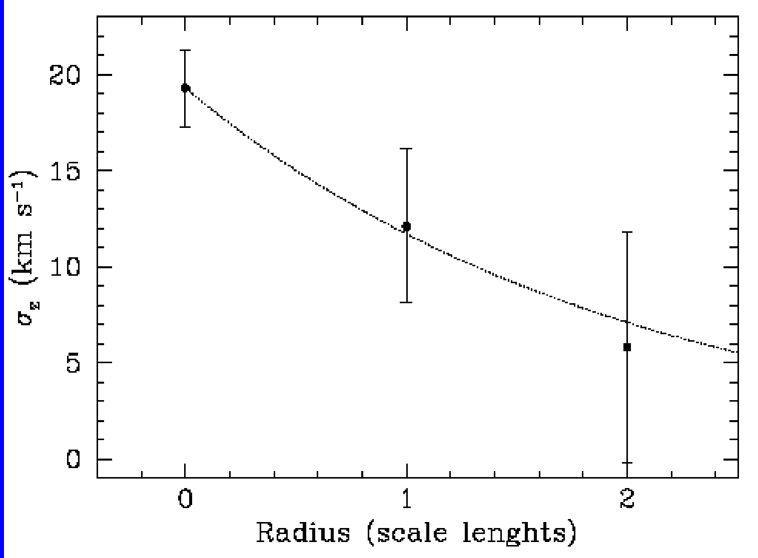
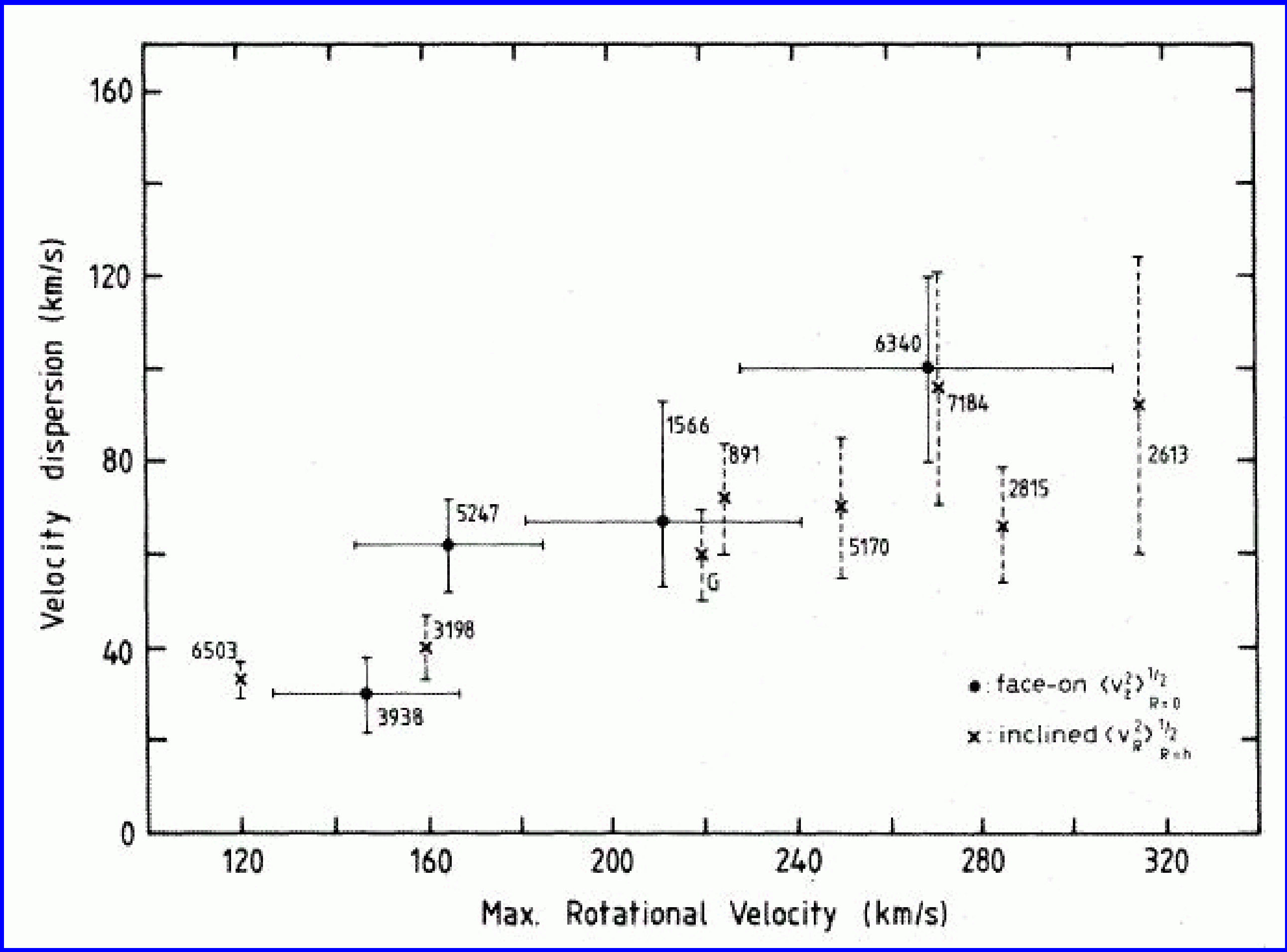


Figure 3: Vertical velocity dispersion σ_z as a function of radius. The dotted line represents the expected radial decline for a disk with constant thickness and constant stellar mass-to-light ratio.

However, Gerssen *et al.* (1997) could not confirm it in NGC 488: they suggest that the scale-length in B is not representative for the mass distribution.

It is important to obtain K-band surface photometry for NGC 488 and the other galaxies in Bottema's sample.



Bottema also found from a sample of 12 galaxies that the (extrapolated) vertical dispersion at the center and the radial one at 1 scalelength

$$\sigma_{z,0} = \sigma_{R,h_R} = (0.29 \pm 0.10) V_{max},$$

where V_{max} is the rotation velocity in the flat part of the rotation curve.

Even the late-type dwarf UGC 4325 was found to follow this relation (Swaters, Ph.D. thesis, 1999) ($\sigma_{\mathrm{R,h_R}} \sim 20$ km/s, $V_{\mathrm{max}} \sim 90$ km/s).

It probably arises as follows:

For a flat rotation curve we have for the epicyclic frequency

$$\kappa = \sqrt{2}\frac{V_{\mathrm{max}}}{R}.$$

Use the equation for the parameter Q for local stability from Toomre (1964)

$$Q = \frac{\sigma_{\mathrm{R}}\kappa}{3.36 G\Sigma},$$

and a Tully-Fisher relation

$$L \propto V_{\mathrm{max}}^{n}$$

with $n = 4$.

Then

$$\sigma_{\mathrm{R,h_R}} \propto Q \left(\frac{M}{L}\right) \sqrt{\mu_\circ}\ V_{\mathrm{max}}.$$

Here $\mu_\circ$ is the central face-on surface brightness in linear units ($L_\odot \mathrm{pc}^{-2}$).

So the Bottema relation implies that

$$Q \left(\frac{M}{L}\right) \sqrt{\mu_\circ} \sim \text{ constant},$$

even for low surface brightness dwarfs.

Observations of course allow a substantial scatter in the constant (or the individual parameters) among galaxies.

For "normal" disks obeying "Freeman's law" ($\mu_\circ \rightarrow 21.7$ B-mag arcsec^{-2}) this reduces to

$$Q \left(\frac{M}{L}\right)_{\mathrm{B}} \sim 6.$$

$\mu_\circ$ and M/L refer to the old disk population.

If we ignore for the moment the (dynamical) influence of the gas, it can be shown (van der Kruit & de Grijs, 1999) that at $R = 1h_{\rm R}$

$$\sigma_{\rm R,h} = (0.48 \pm 0.02) Q \frac{\sigma^2_{\rm z,h}}{V_{\rm max}} \frac{h_{\rm R}}{h_{\rm z}}.$$

Here again the "uncertainty" in the coefficient relates to the range of vertical density distributions above.

With the Bottema relation this reduces to

$$\left(\frac{\sigma_{\rm z}}{\sigma_{\rm R}}\right)^2_{\rm R=h_R} = \frac{(7.2 \pm 2.5)}{Q} \frac{h_{\rm z}}{h_{\rm R}}.$$

In the solar neighborhood the axis ratio of the velocity ellipsoid is $\sigma_{\rm z}/\sigma_{\rm R} \sim 0.5$ (Dehnen & Binney, 1998).

Assuming that this also holds at $R = 1h_{\rm R}$ and using $h_{\rm z} \sim 0.35$ kpc and $h_{\rm R} \sim 4$ kpc, it follows that

$$Q \sim 2.5.$$

The thickness of the HI-layer can be used to estimate the surface mass density of the disk.

It is known from 21-cm observations of face-on galaxies (e.g. van der Kruit & Shostak, 1984) that the velocity dispersion of the gas $\sigma_{\mathrm{HI}} = 8 - 10$ km s^{-1}.

$$(\mathrm{FWHM})_{\mathrm{HI}} = (2.8 \pm 0.2)\sigma_{\mathrm{HI}}\sqrt{\frac{h_{\mathrm{z}}}{2\pi G\Sigma(R)}}.$$

Another estimate of the disk mass M_{D} follows from the global stability criterion of Efstathiou *et al.* (1982)

$$Y = V_{\mathrm{max}}\sqrt{\frac{h_{\mathrm{R}}}{GM_{\mathrm{D}}}} \sim 1.1.$$

For a pure exponential disk mass distribution the maximum in the rotation curve (Freeman, 1970) occurs at $R \sim 2.2 h_{\rm R}$ with an amplitude

$$V_{\rm max}^{\rm disk} = 0.88\sqrt{\pi G \Sigma(0) h_{\rm R}}.$$

Hydrostatic equilibrium at the center gives

$$\sigma_{\rm z,0}^2 = (5.0 \pm 0.2) G \Sigma(0) h_{\rm z}.$$

Therefore

$$V_{\rm max}^{\rm disk} = (0.69 \pm 0.03) \sigma_{\rm z,0} \sqrt{\frac{h_{\rm R}}{h_{\rm z}}}.$$

With the Bottema relation then we get

$$\frac{V_{\rm max}^{\rm disk}}{V_{\rm max}} = (0.21 \pm 0.08) \sqrt{\frac{h_{\rm R}}{h_{\rm z}}}.$$

So, the flattening of the disk can be used to test the "maximum disk hypothesis".

OBSERVATIONS OF DISKS

The most extensive study of the photometric disk parameters in the optical and near-IR is that of a statistically complete sample of 86 disk dominated galaxies in the thesis of Roelof de Jong (1995).

Some of his conclusions are:

- Freeman's law is really an upper limit to the central surface brightness.

- The scalelength does not correlate with Hubble type.

- In disks fainter regions are generally bluer, probably resulting from a combination of stellar age and metallicity gradients.
  Outer regions are on average younger and of lower abundance.

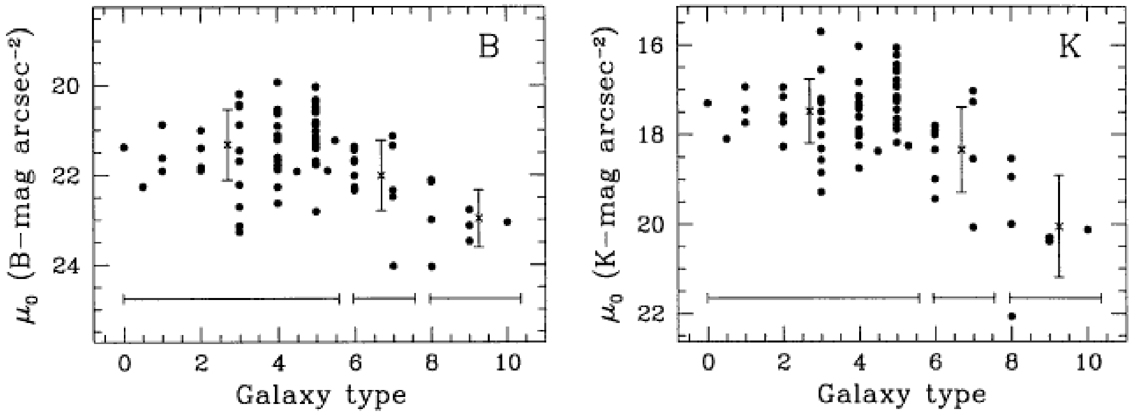


Fig. 3. The Galactic extinction corrected central surface brightness of the disks as a function of morphological RC3 type. The crosses show the values averaged over the bins indicated by the horizontal bars. The vertical bars indicate the standard deviations of the mean values.

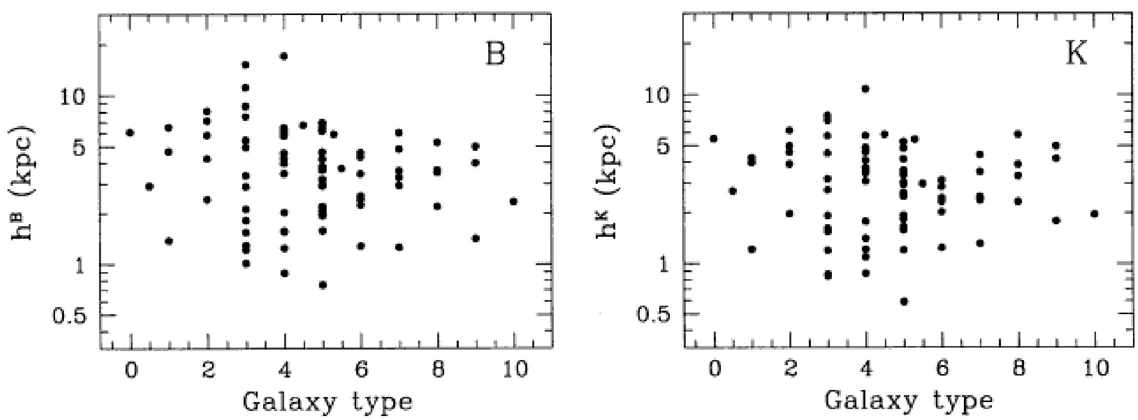


Fig. 4. The scalelength of the disk as a function of morphological type.

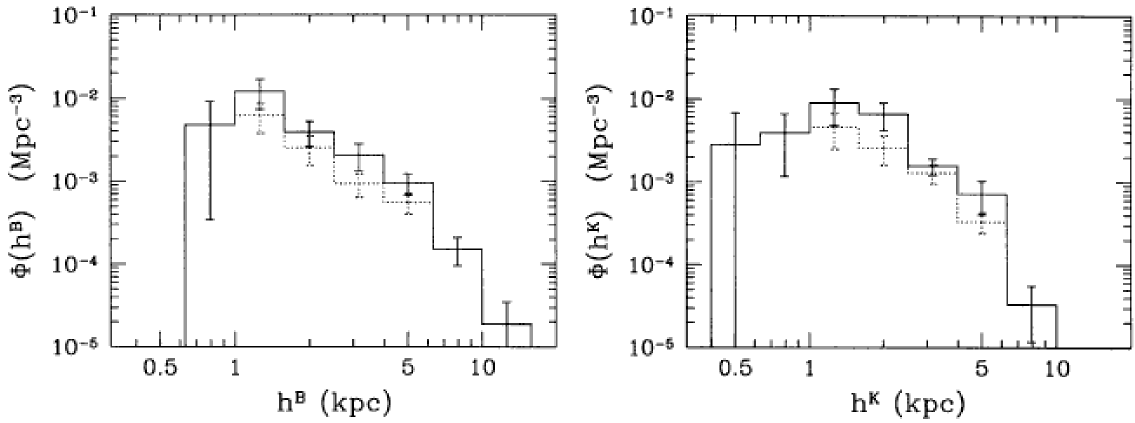


Fig. 9. The volume corrected distribution of the disk scalelengths. The dashed line indicates the distribution for type earlier than T=6. The number density is per bin size, which is in steps of 0.2 in $\log(h)$.

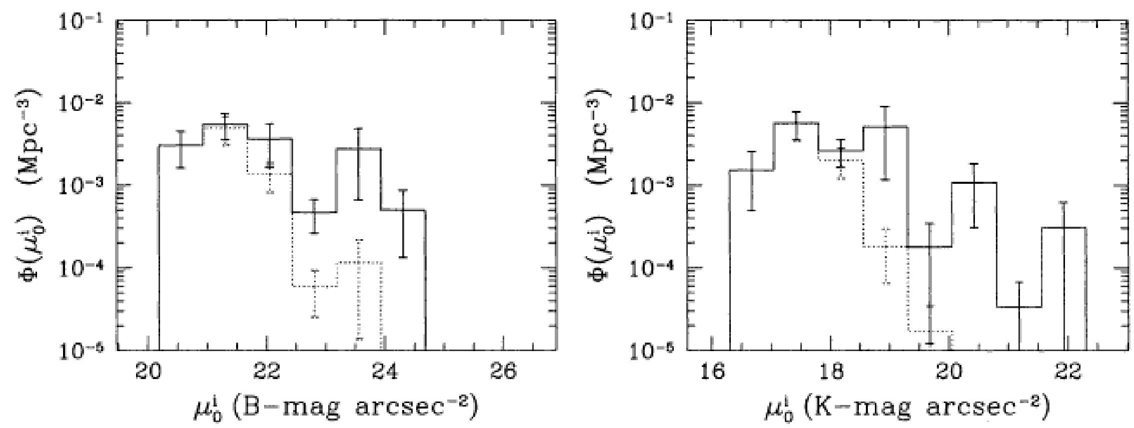


Fig. 8. The volume corrected distribution of the central surface brightness. The dashed line indicates the distribution for types earlier than type T=6. The number density is per bin size, which is in steps of 0.75 mag arcsec^{-2} in μ_0.

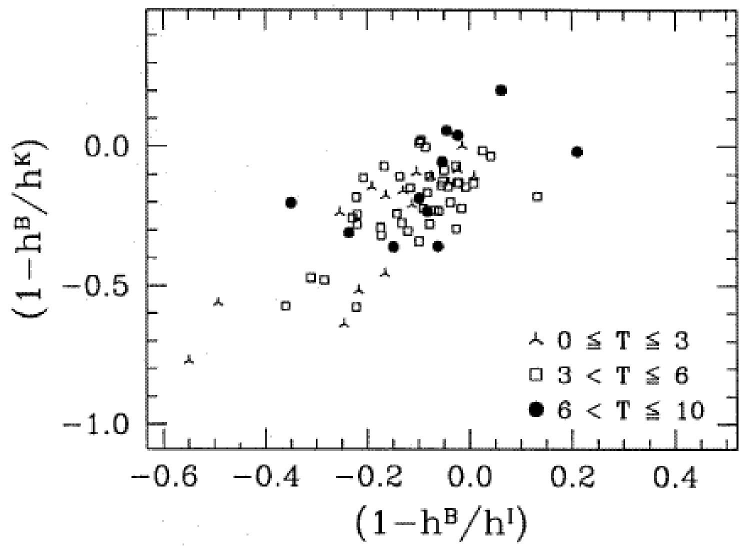


Fig. 9. The difference in scalelength between the different passbands. Only points with errors smaller than 0.15 are plotted. Different symbols are used to denote the indicated morphological types.

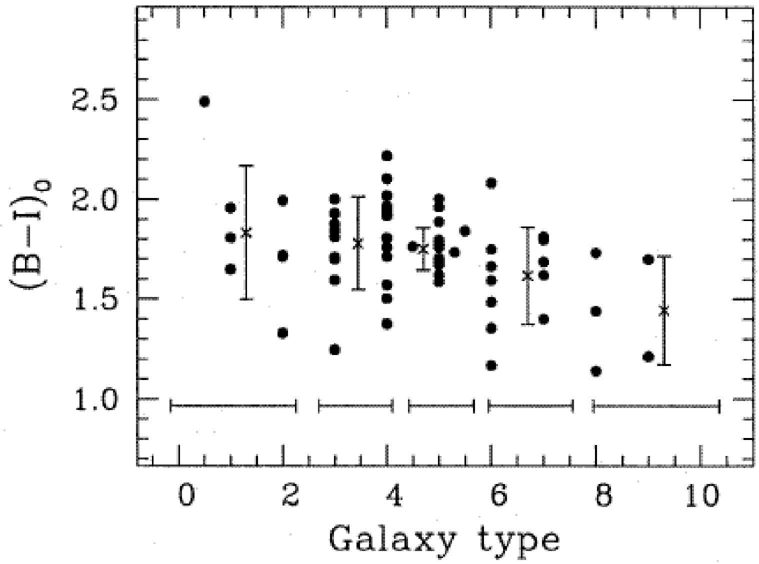


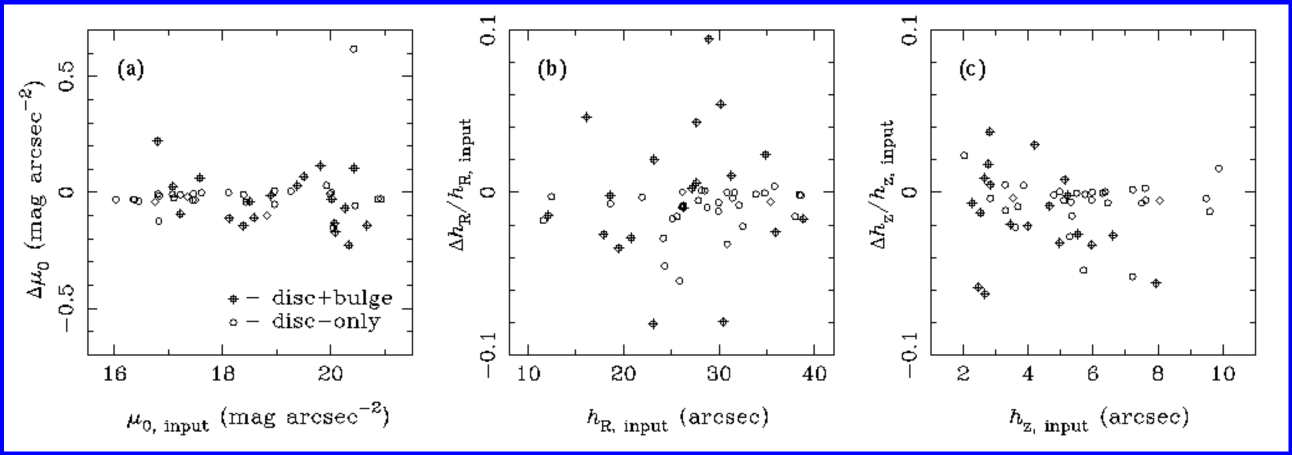
Fig. 10. The Galactic reddening corrected integrated B–I colors of the galaxies as function of morphological type index. The crosses show the values averaged over the bins indicated by the horizontal bars. The vertical bars are the standard deviations on the mean values. Only the galaxies with an error of less than 0.5 mag in their color were used.

In his thesis Richard de Grijs (1997) presented optical and near-IR surface photometry of a sample of 47 edge-on galaxies.

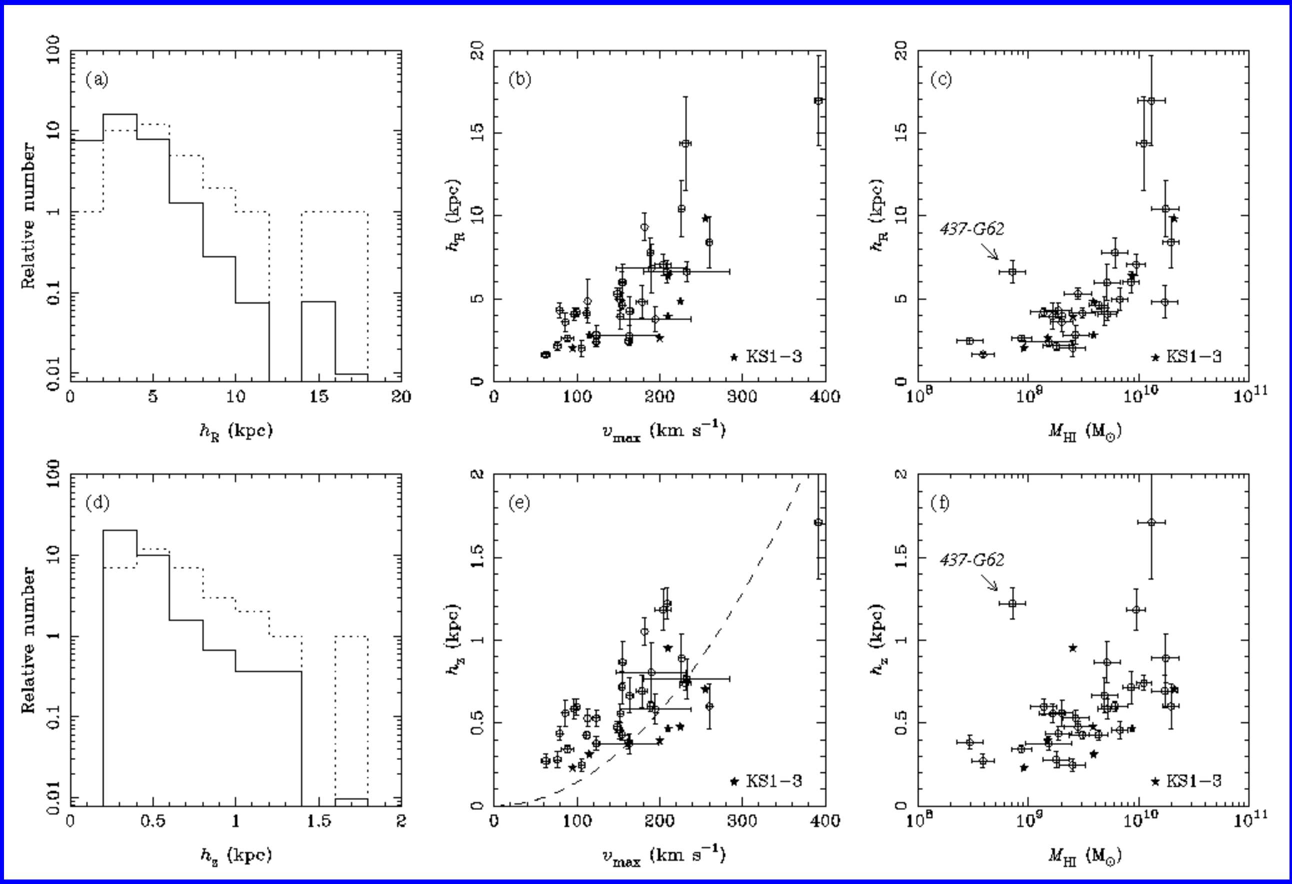
The maps have recently been re-analysed by Kregel, van der Kruit & de Grijs with an improved 2-D fitting procedure.

This procedure shows on test images a very good recovery rate of the parameters.

The worst errors occur not surprisingly for low surface brightness disks.



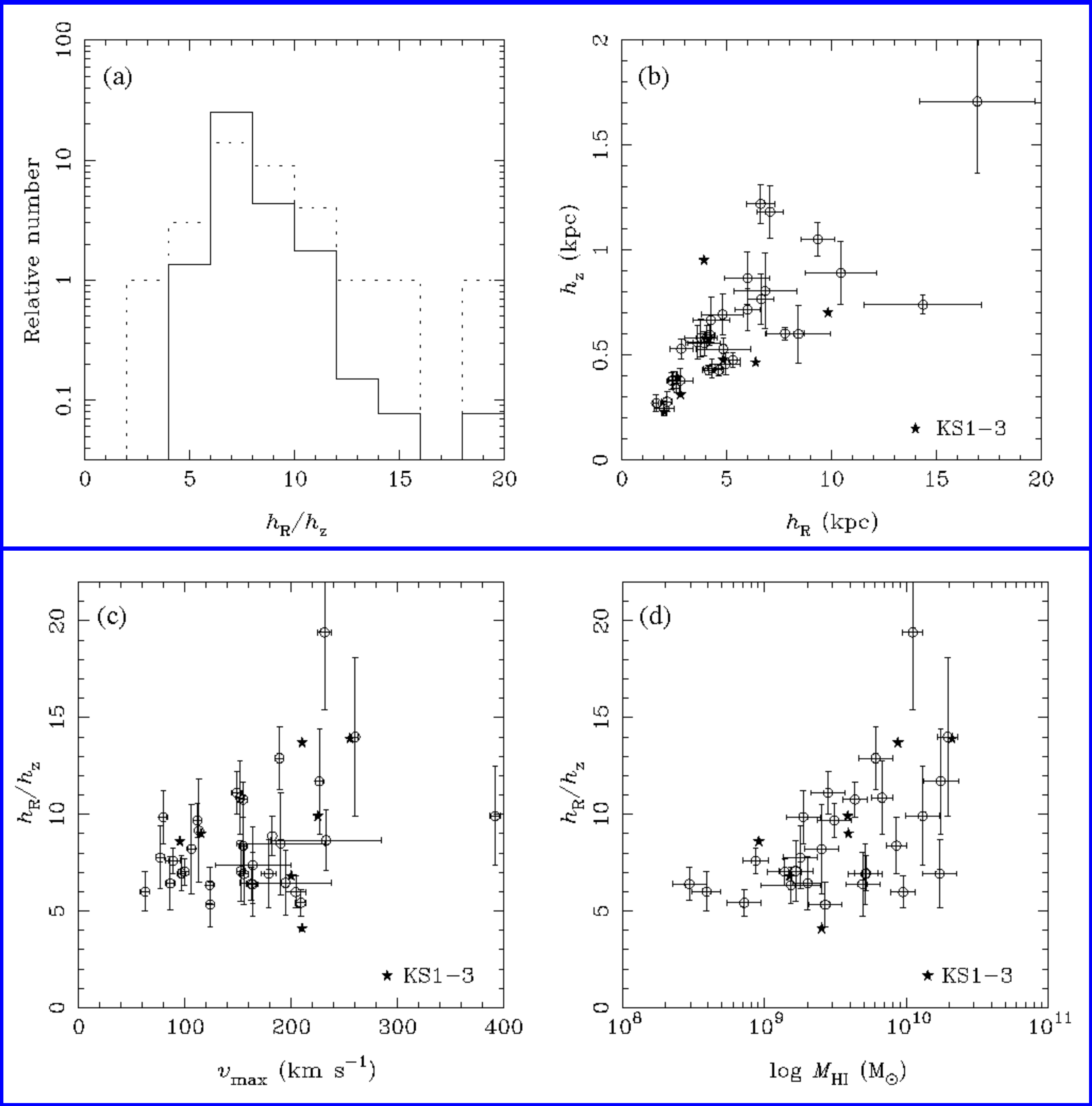
Some results:



- Both the scalelength and the scaleheight correlate in general terms with the rotation velocity.

- For h_R this is expected from the Tully-Fisher relation.

- Our Galaxy would be somewhat unusual if the scalelength is as small as 2 to 2.5 kpc as some recent studies claim.


(a)
Relative number
h_R/h_z
(b)
h_z (kpc)
h_R (kpc)
KS1−3
(c)
h_R/h_z
v_{max} (km s^{-1})
KS1−3
(d)
h_R/h_z
log M_{HI} ($M_\odot$)
KS1−3

The flattening of the sample after volume correction is

$$\frac{h_{\mathrm{R}}}{h_{\mathrm{z}}} = 7.3 \pm 2.2.$$

This implies

$$\frac{V_{\mathrm{max}}^{\mathrm{disk}}}{V_{\mathrm{max}}} = 0.57 \pm 0.22.$$

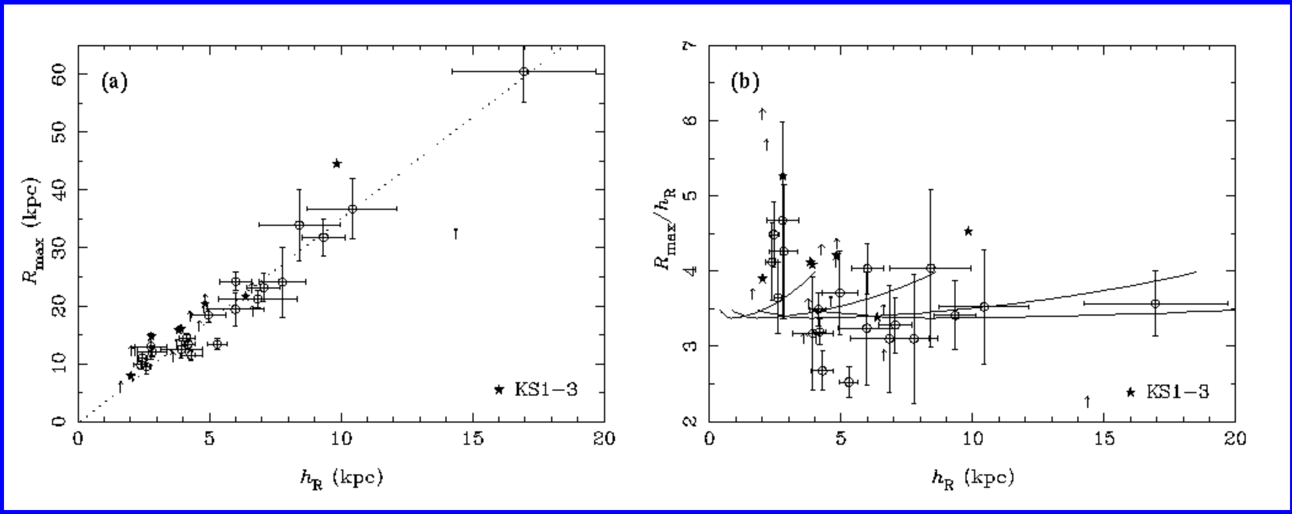
Most galaxies are not “maximum disk”.

Bottema (1993) derived a similar relation applicable to face-on galaxies, where no scaleheight can be measured:

$$V_{\mathrm{max}}^{\mathrm{disk}} = 0.88\sigma_{\mathrm{z,0}}\sqrt{\frac{h_{\mathrm{R}}}{z_{\mathrm{o}}}}.$$

Then he concluded from his sample that

$$\frac{V_{\mathrm{max}}^{\mathrm{disk}}}{V_{\mathrm{max}}} = 0.63 \pm 0.17.$$



- At least 20 of the spirals show radial truncations.

- The ratio of the truncation radius and the scalelength is on average

$$\frac{R_{\mathrm{max}}}{h_{\mathrm{R}}} = 3.6 \pm 0.6.$$

- But large galaxies have smaller values for this ratio.

- For common disks with scalelengths of 5 kpc or less, the ratio is about 4.

The truncation radius in a simple view results from the maximum specific angular momentum of the sphere from which the disk collapsed.

In a simple model van der Kruit (1987) predicted a value of 4.5 for the observed ratio, based on a Peebles spin parameter $\lambda = J|E|^{1/2}G^{-1}M^{-5/2}$ of 0.7.

Dalcanton *et al.* (1997) have extended this to a models with a dispersion in the spin parameter.

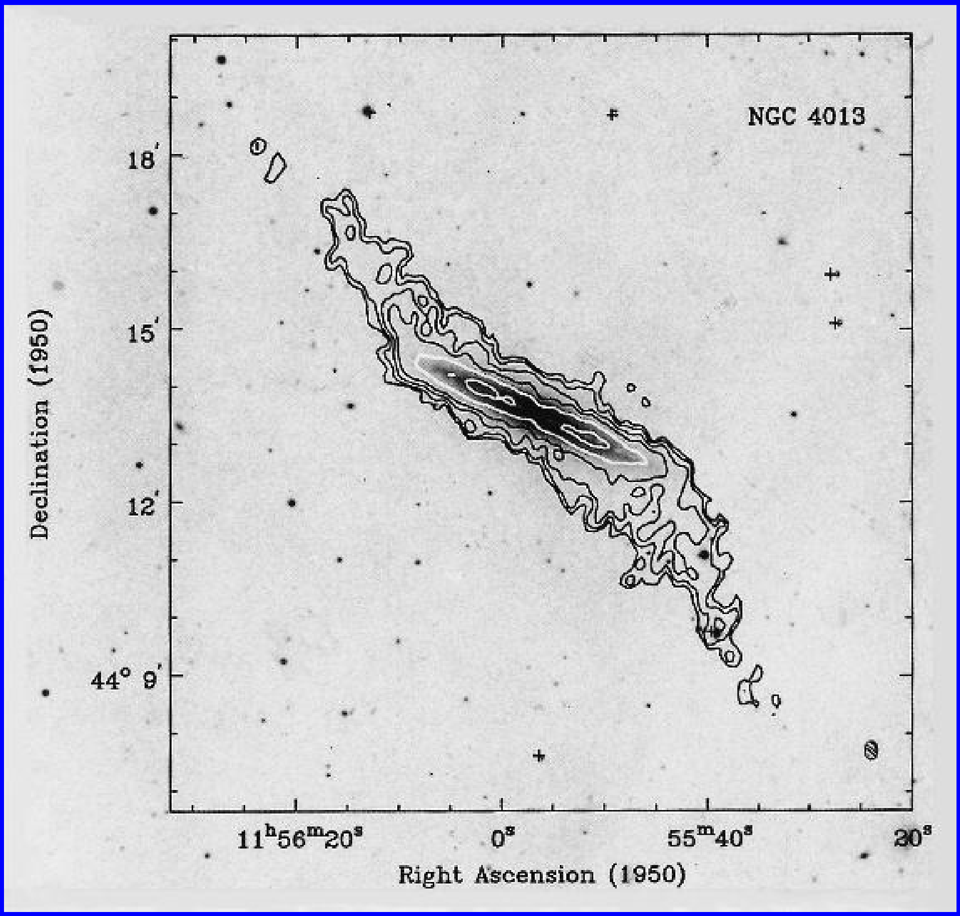
We have calculated model surface density profiles with the Dalcanton *et al.* method for $M_{\rm tot} = 10^{10} - 10^{13} M_{\odot}$ and $\lambda = 0.01 - 0.28$.

These are the lines in the figures.

For completeness I mention that in many cases there is a warp in the HI-layer in the outer parts.

These warps often start roughly at the truncation radius.

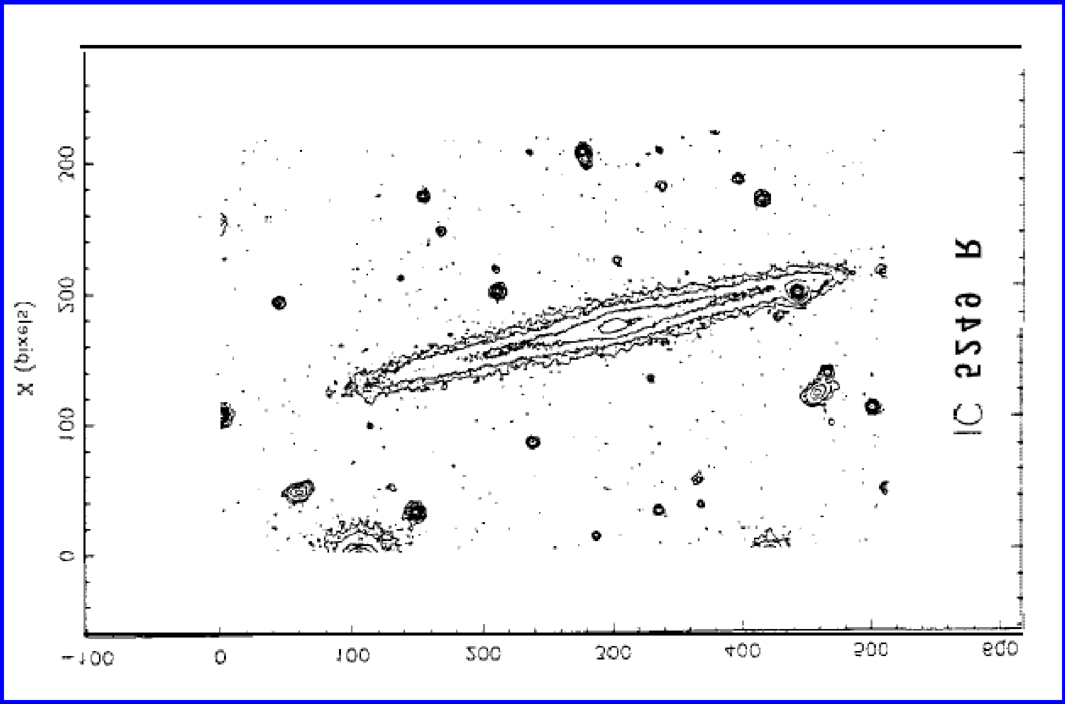
This suggest that the material in the warp has been accreted subsequent to disk formation.

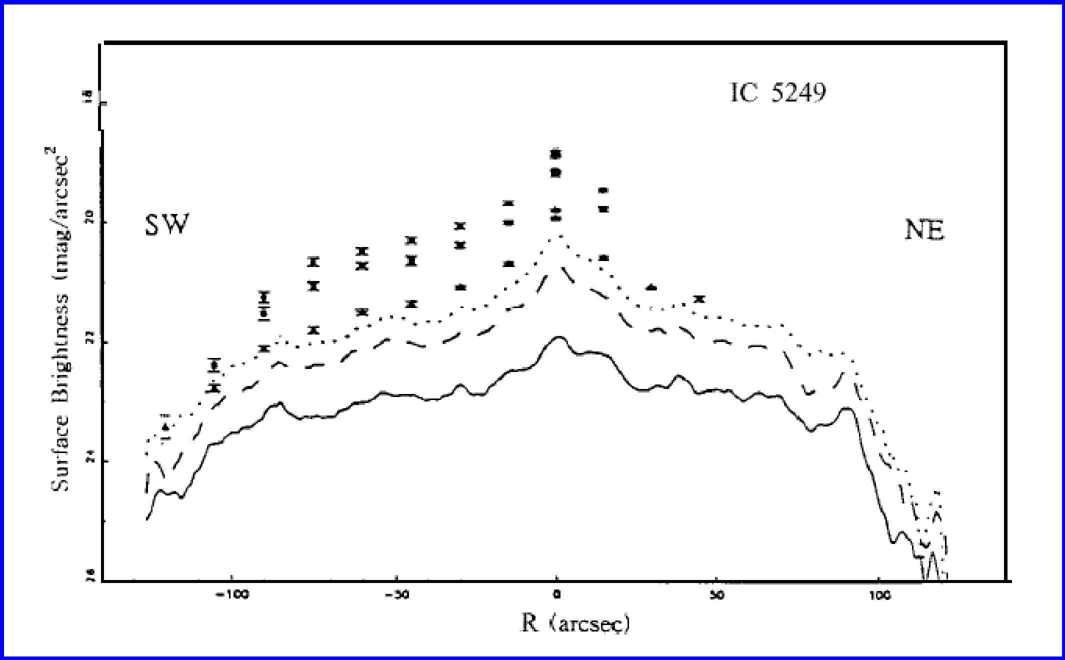


IC 5249

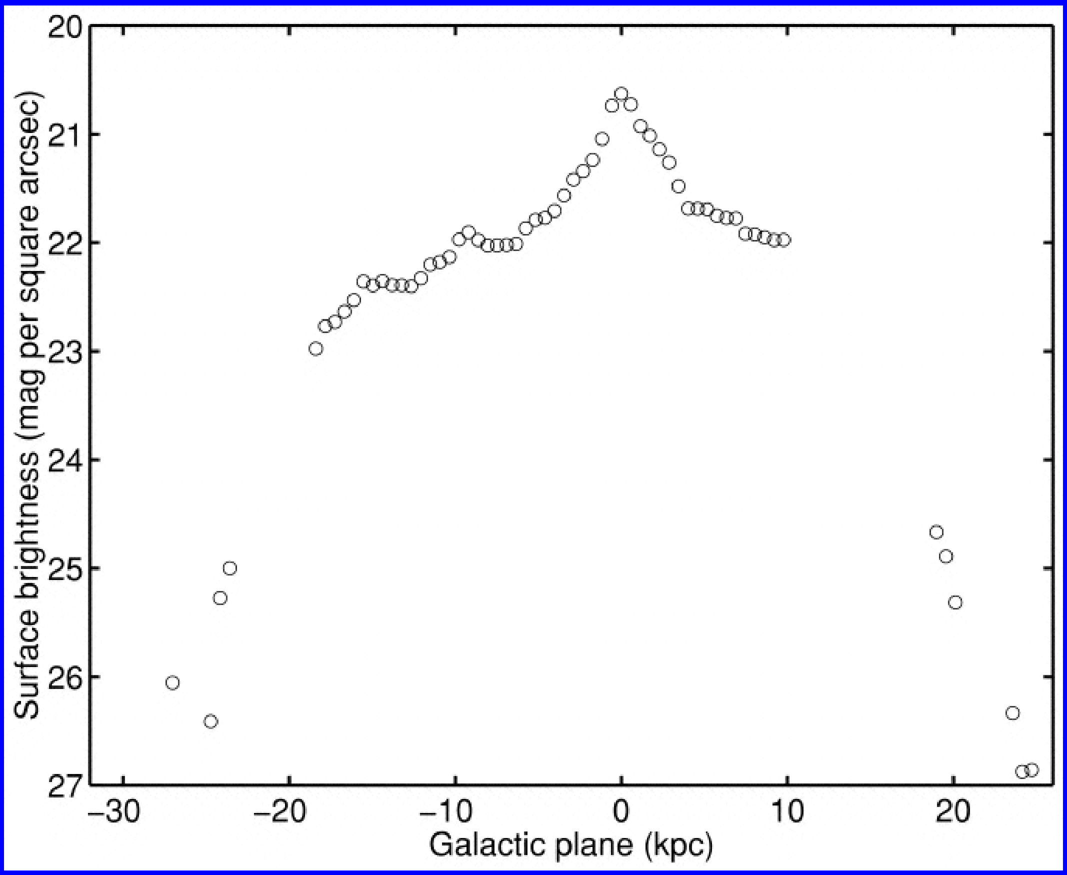
The "superthin" disk galaxy IC 5249 has recently been studied by van der Kruit, Jiménez-Vicente, Kregel & Freeman.

We re-analyse the ATCA HI observations of Abe *et al.* (1999), use their photometry and that of Claude Carignan, Richard Wainscoat and Yong-Ik Byun, and obtained an optical spectrum to measure the stellar kinematics.





Here are the R-band isophote map from Byun and the major axis surface brightness profiles in (bottom to top) in B, R and I from Byun and in J, H and K from Wainscoat.

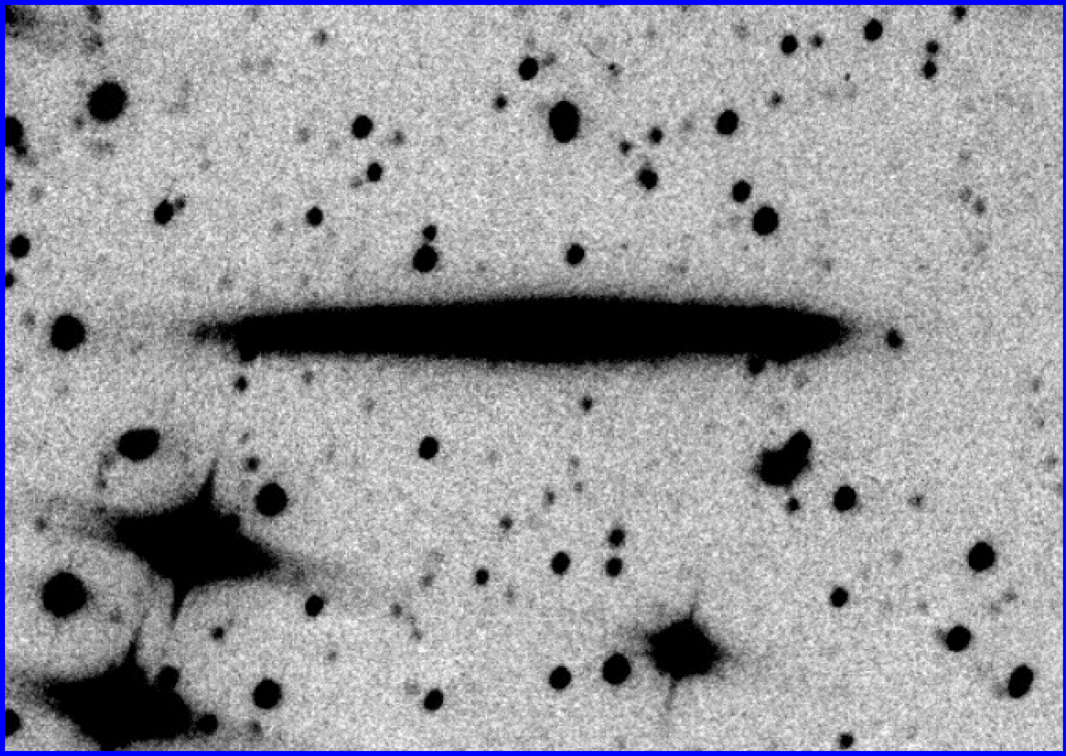


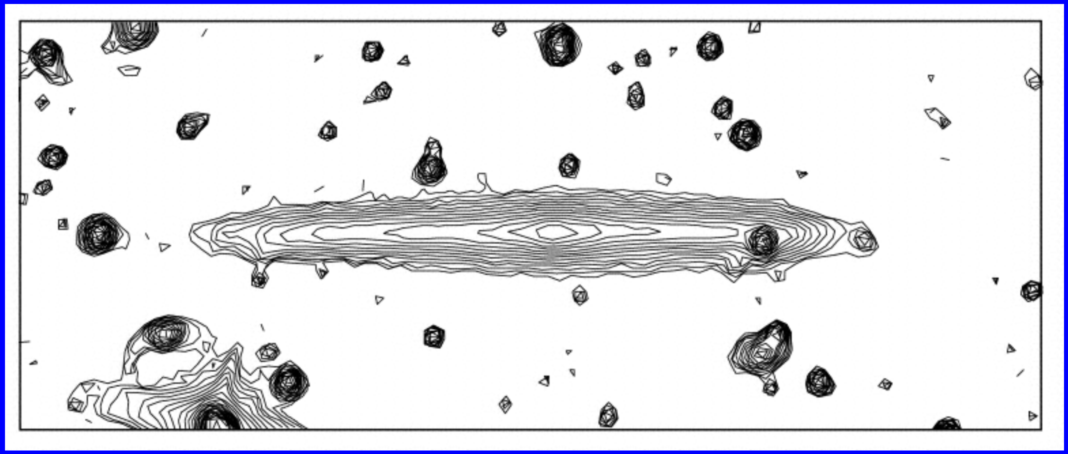
The major axis profile (here in R from Abe *et al.*) shows a long scalelength and a very sharp truncation.

We argue that the central spike is *not* a bulge, but rather structure in the disk. This is mostly based on the observation that the minor axis profile and vertical profiles of the disk are entirely similar.

On deep exposures IC 5249 is not quite so thin.

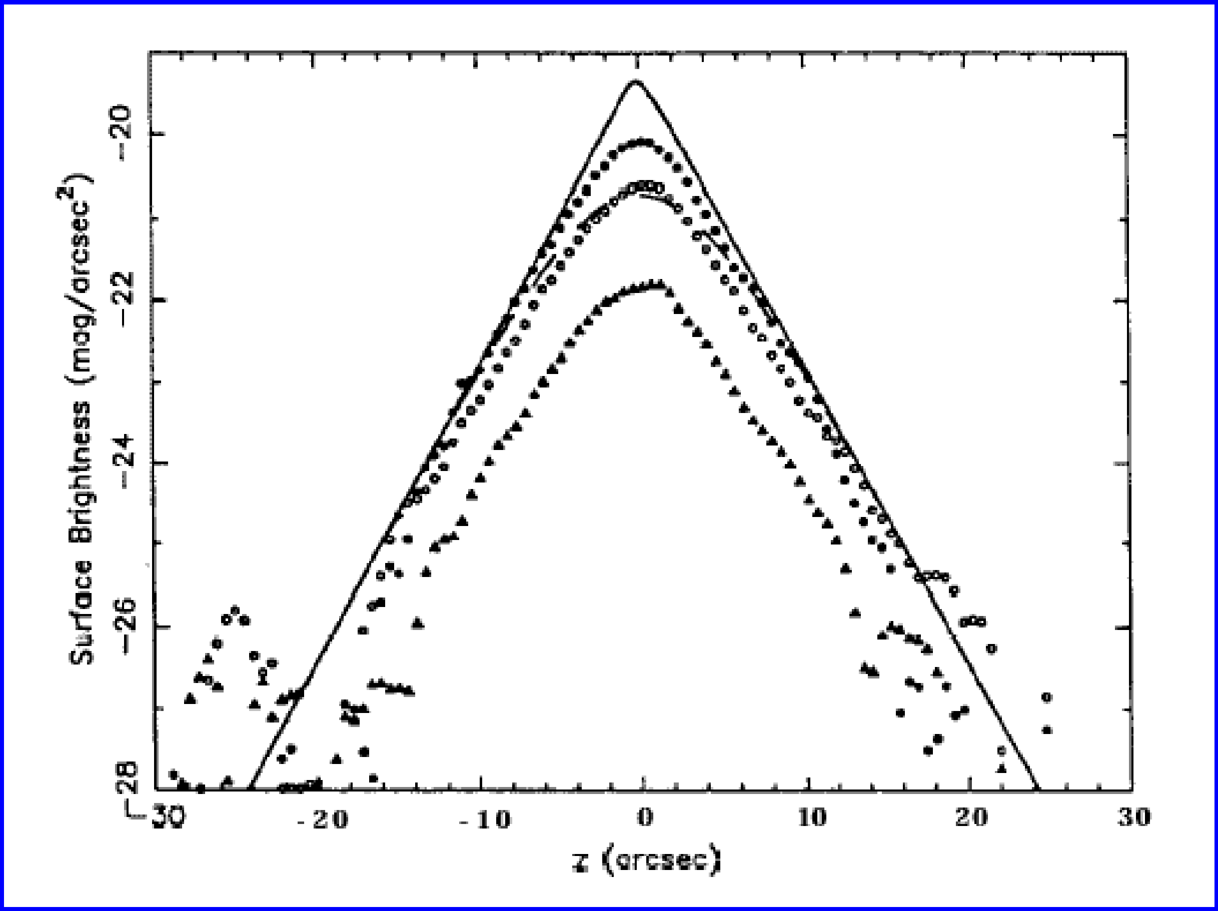
Here this can be seen in the image and isophote map of Abe *et al.*.

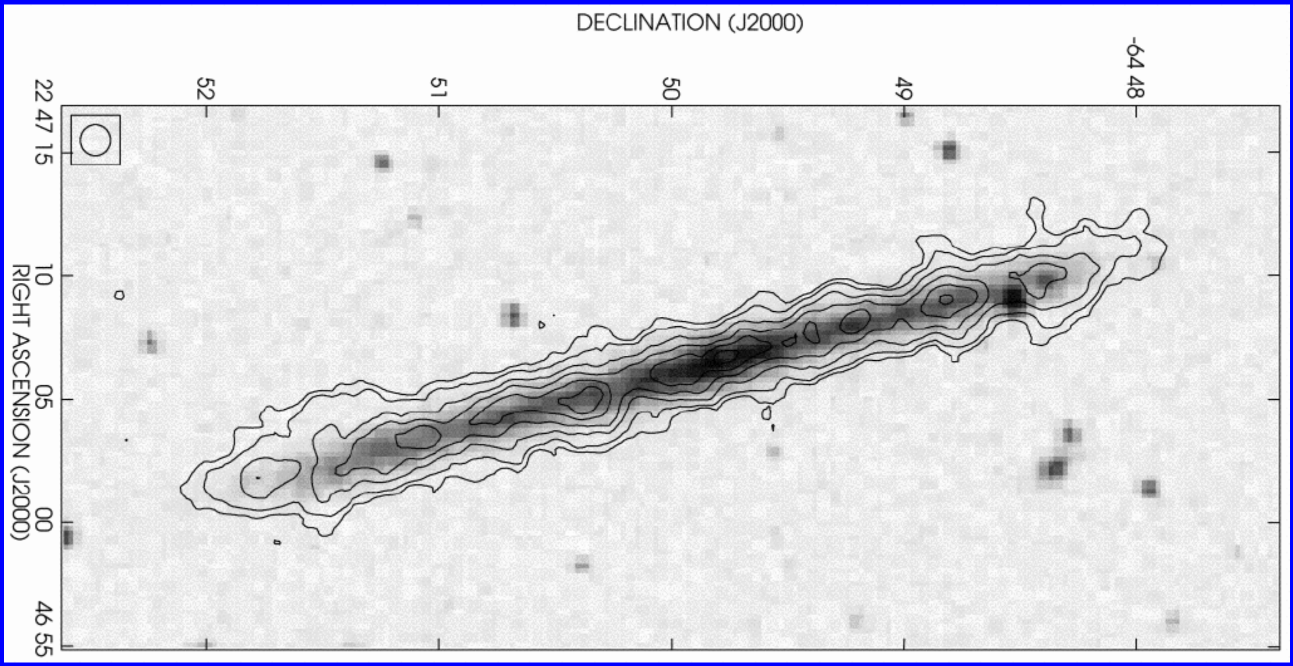




We adopt a scalelength of $h_R = 7 \pm 1$ kpc and a truncation radius of $R_{max} = 17 \pm 1$ kpc.

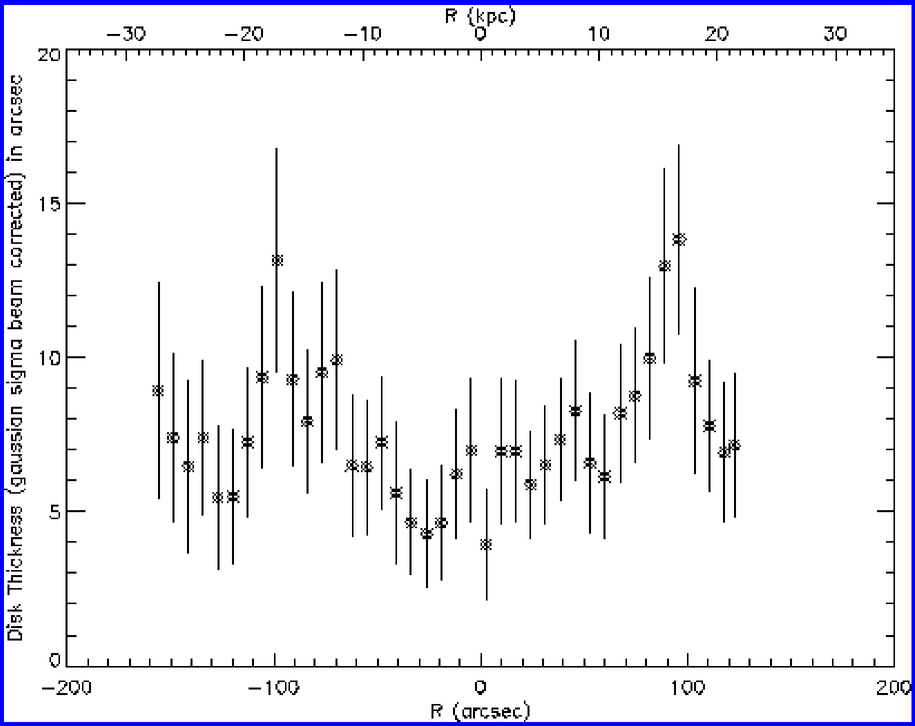
The disk can in the vertical direction be fitted very well with a sech-function and the vertical scaleheight is $h_z = 0.65 \pm 0.05$ kpc at all radii and in all colors.

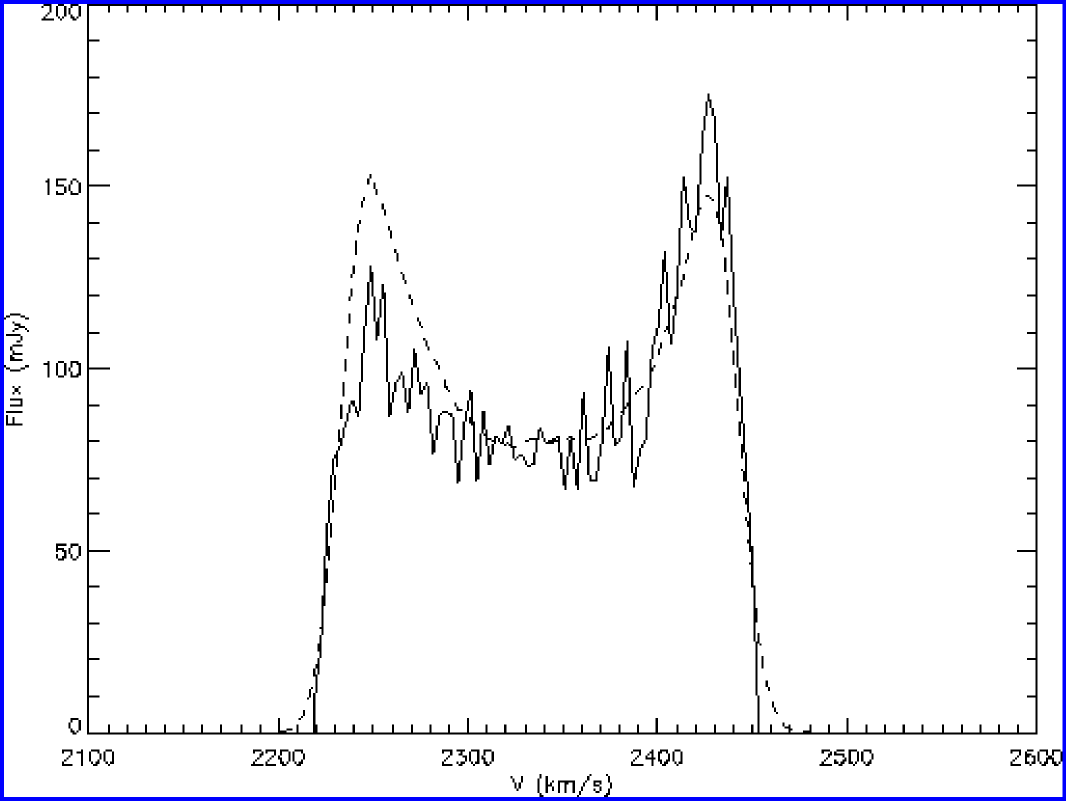




The HI ATCA-map of Abe *et al.* shows a fairly uniform surface density along the disk.

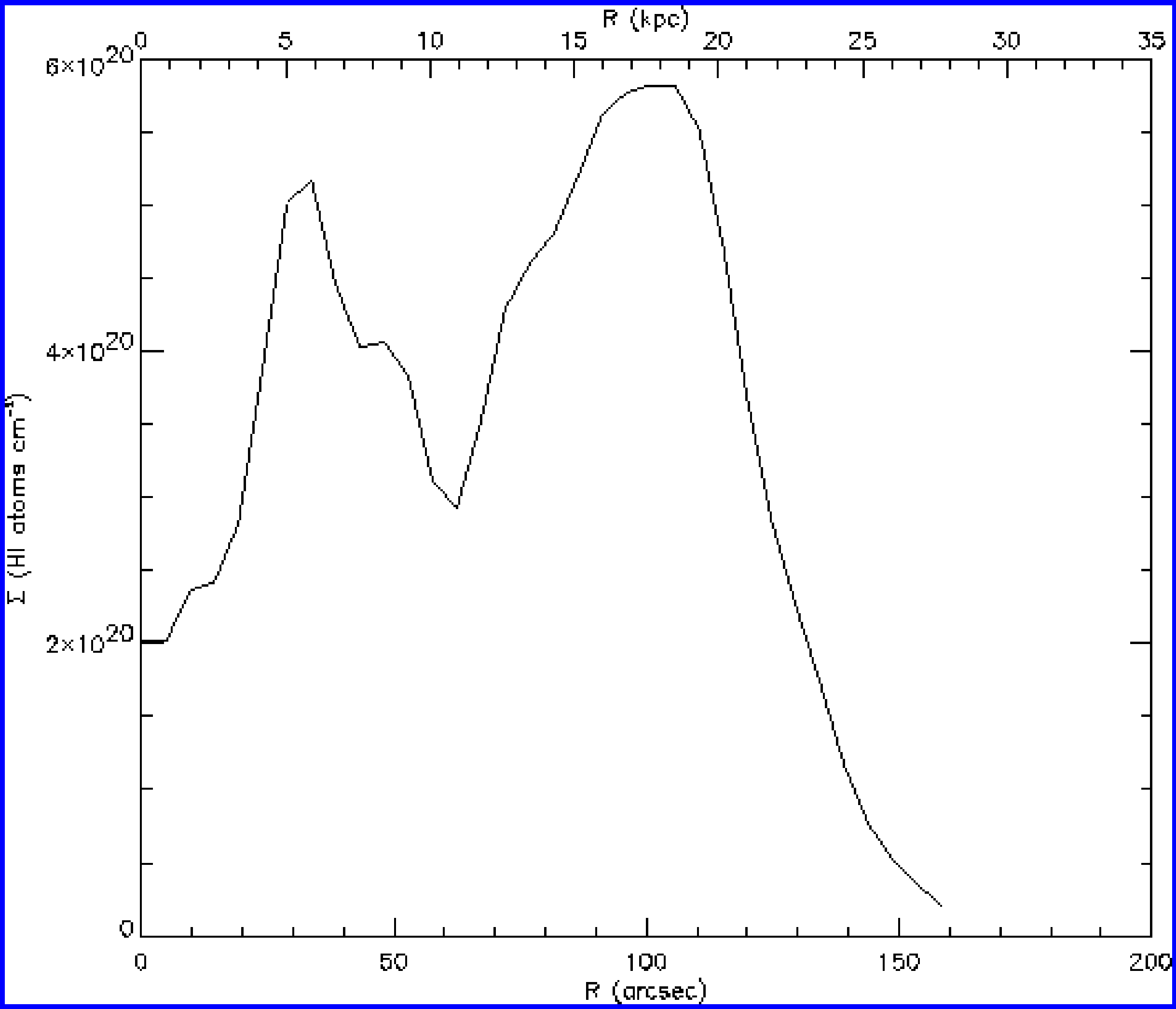
In the outer parts there is some evidence for a small flaring.



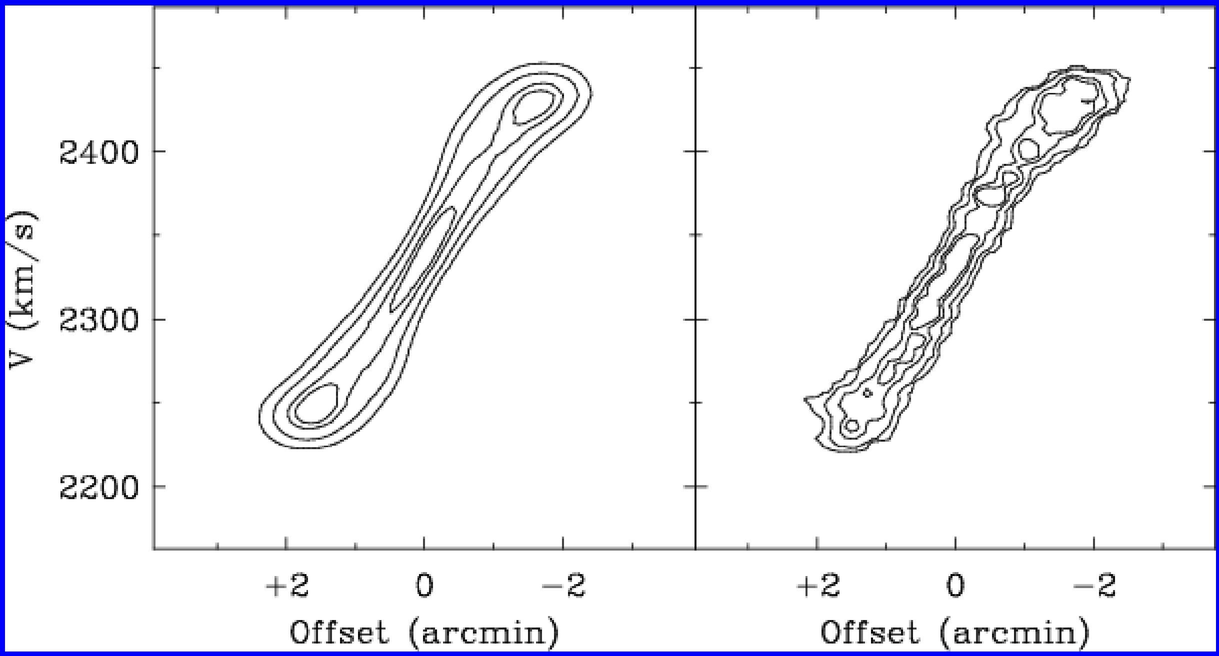


Abe *et al.* derived a rotation curve that has essentially solid body rotation. This is inconsistent with the rather uniform surface density and the observed clearly double-peaked integrated HI-profile.

The Abe *et al.* rotation curve was determined from a first moment analysis in the (x,V)-plane. This is dangerous.

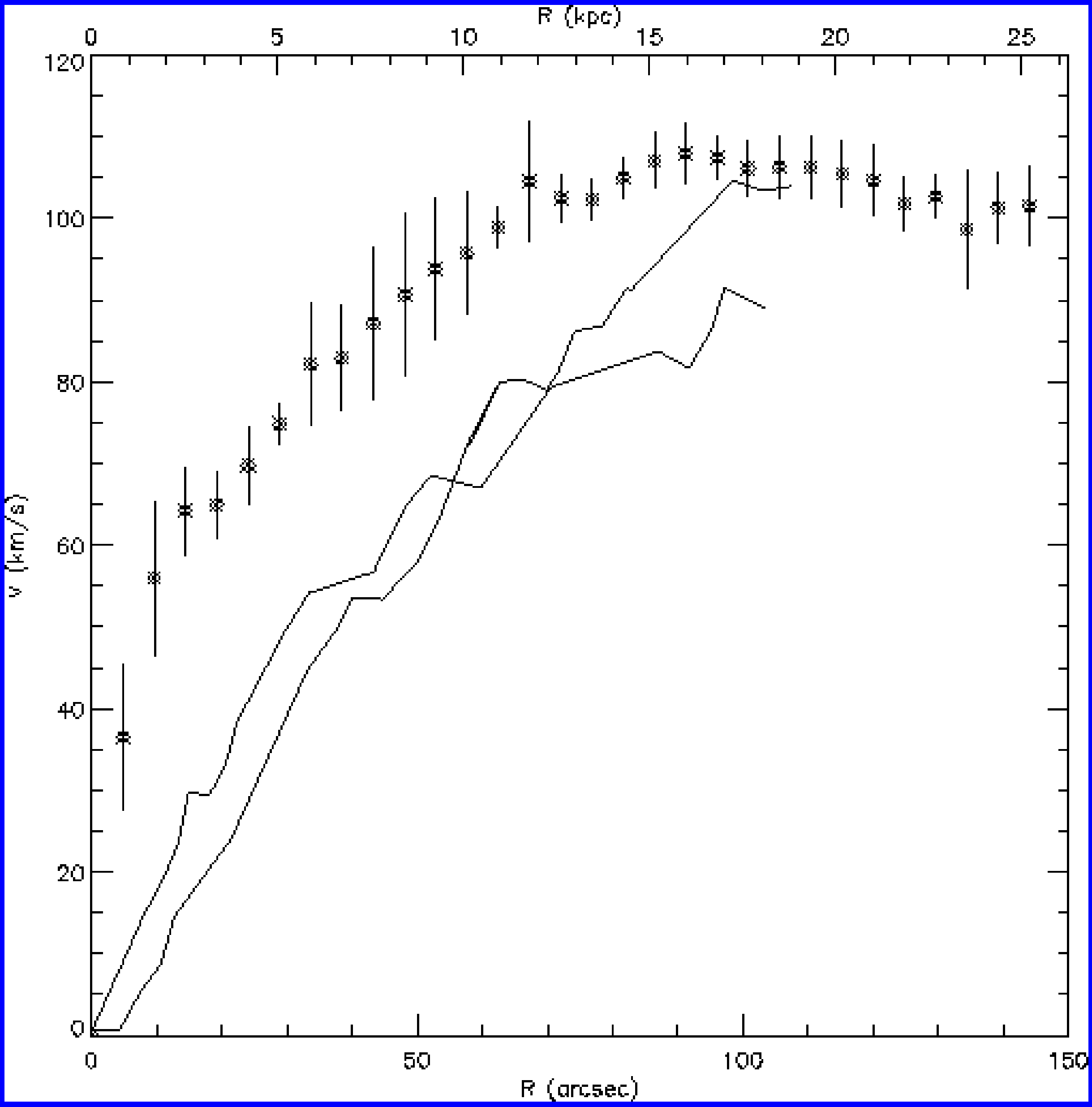


In our analysis we first decomposed the observed surface density along the disk into a radial distribution under the assumption or circular symmetry.



We then in the usual way modelled with this (x,V)-diagram with various rotation curves until a best fit to the observations was obtained. The fit shows that $\sigma_{\mathrm{HI}} = 7 - 8$ km/s.

This resulted in a completely different rotation curve than the one by Abe *et al.*, rising initially to a maximum and then remaining flat.


R (kpc)
0
5
10
15
20
25
120
100
80
60
40
20
0
v (km/s)
0
50
100
150
R (arcsec)

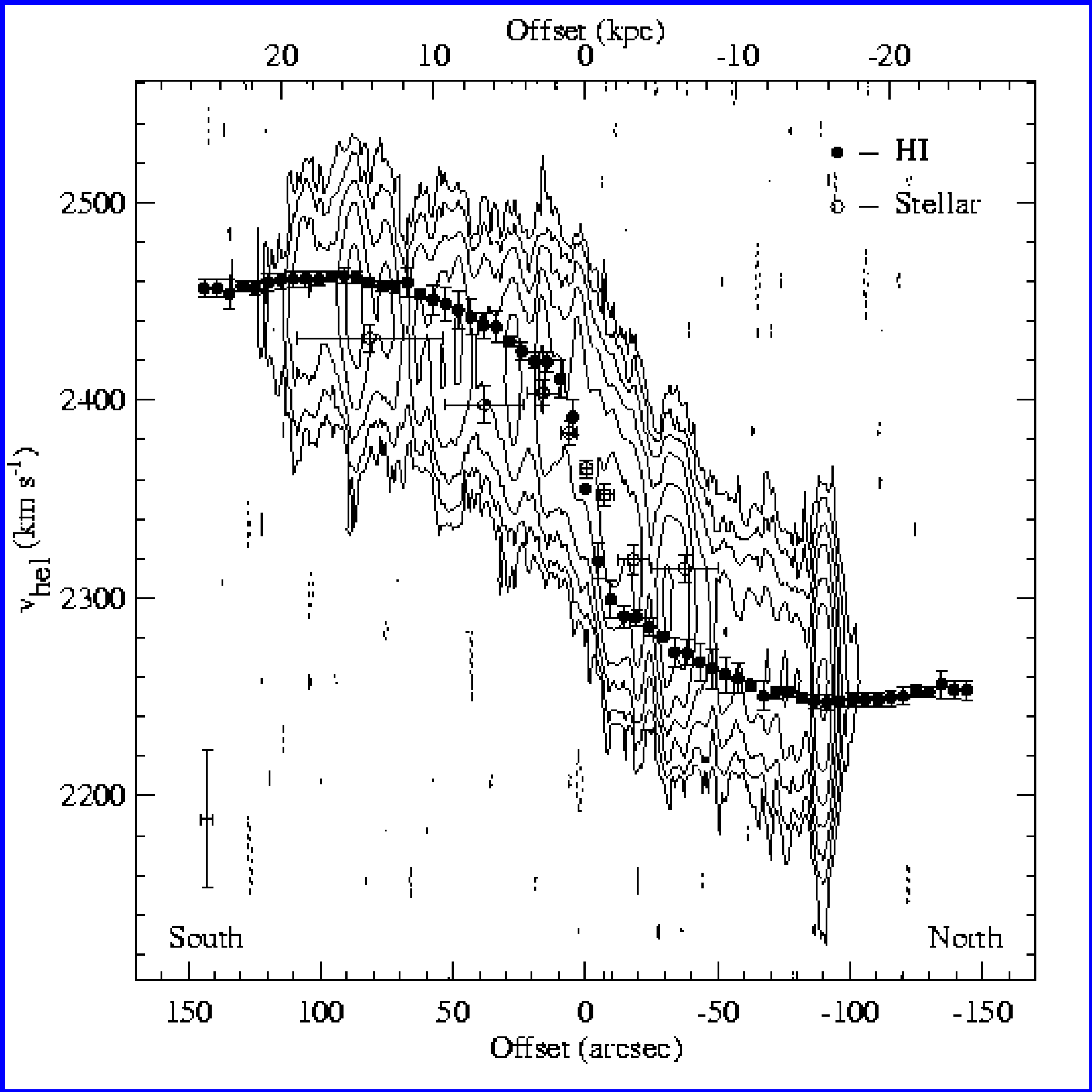
The optical spectrum was taken with the Double Beam Spectrograph at the ANU 2.3-meter telescope at Siding Spring for a total of 16,000 seconds.

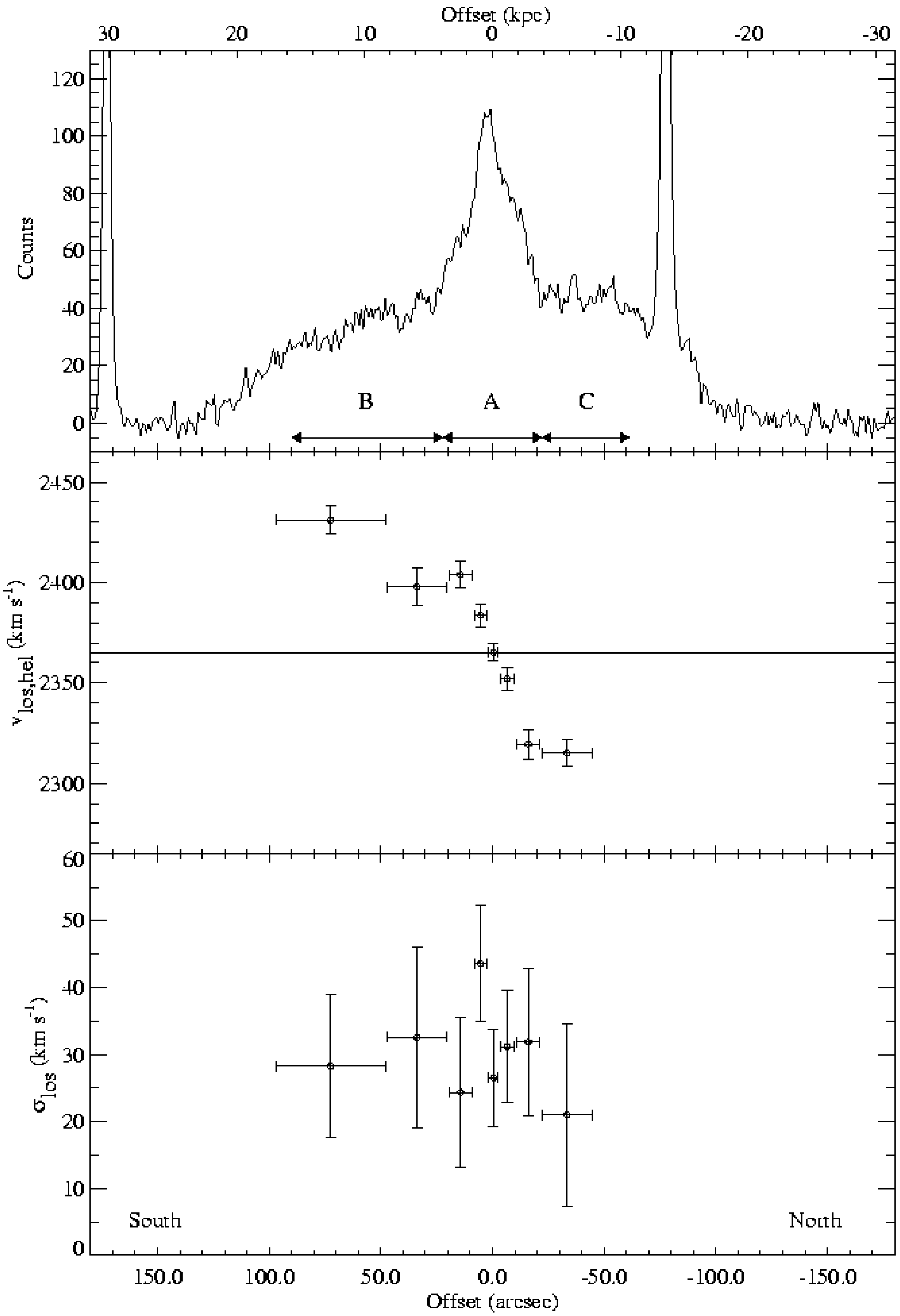
The red arm observed Hα, [NII] and [SII]. We used this to compare to the HI data.

It follows that at this wavelength we are looking at least halfway through the galaxy, as the Hα follows the ridge of the HI in the (x,V)-plane.

The blue arm observed the Mgb-triplet and various Fe-lines and was used to measure the stellar kinematics.

From this (after allowing for the line-of-sight integration) we find a tangential stellar velocity dispersion $\sigma_\theta = 25 - 30$ km/s.


Offset (kpc)
20
10
0
-10
-20
● — HI
○ — Stellar
2500
2400
2300
2200
v_{hel} (km s^{-1})
South
North
150
100
50
0
-50
-100
-150
Offset (arcsec)


Offset (kpc)
30
20
10
0
-10
-20
-30
Counts
120
100
80
60
40
20
0
B
A
C
2450
2400
2350
2300
$v_{los,hel}$ (km s^{-1})
60
50
40
30
20
10
0
σ_{los} (km s^{-1})
South
North
150.0
100.0
50.0
0.0
-50.0
-100.0
-150.0
Offset (arcsec)

Parameters of IC 5249

$h_{\rm R}$	7 ± 1 kpc
$h_{\rm z}$	0.65 ± 0.05 kpc
$\mu_\circ$	~ 24.5 B-mag arcsec^{-2}
$R_{\rm max}$	17 ± 1 kpc
$V_{\rm max}$	105 ± 5 km s^{-1}
$({\rm FWHM})_{\rm HI}$	$\leq 1.1 \pm 0.3$ kpc

Note that $h_{\rm z}$ is larger than that in our Galaxy!

IC 5249 appears on the sky as a very thin disk, because it combines a low surface brightness with a very long scalelength and a truncation radius after only a few scalelengths.

From our data we can derive various kinematical and dynamical properties with the methods given above.

A $({\rm FWHM})_{\rm HI} = 1.1$ kpc and the observed $\sigma_{\rm HI}$ give at $R = 7$ kpc a disk surface density about equal to that observed in HI. So we conclude that the observed width of the HI-layer is due to a small residual inclination of the disk.

	$R = 7$ kpc	$R = 17$ kpc
σ_θ (km/s)	$25 - 30$	$-$
$V_{\rm rot}$ (km/s)	90 ± 5	105 ± 5
$dV_{\rm rot}/dR$ (km/s.kpc)	3 ± 4	0 ± 1
$P_{\rm rot}$ (yr)	5×10^8	1×10^9
A (km/s.kpc)	4.9 ± 1.7	3.1 ± 0.6
B (km/s.kpc)	-7.9 ± 2.7	-3.1 ± 0.6
κ (km/s.kpc)	20 ± 6	3.5 ± 0.4
$P_{\rm epicycle}$ (yr)	$(3 \pm 1) \times 10^8$	$(1.8 \pm 0.4) \times 10^9$
$\sigma_\theta/\sigma_{\rm R}$	0.79 ± 0.23	0.71 ± 0.18
$\sigma_{\rm R}$ (km/s)	35 ± 5	25 ± 5
Asym. drift (km/s)	10 ± 3	$-$
$\Sigma(M_\odot$ pc$^{-2})$	~ 25	~ 6
$\sigma_{\rm z}$ (km/s)	19 ± 4	19 ± 5
Q	~ 2	~ 2
(FWHM)$_{\rm HI}$ (kpc)	0.60 ± 0.17	1.5 ± 0.5

At $R = 7$ kpc the stellar velocity dispersions are similar to the solar neighborhood, but the surface density of the disk is about half of it.

Star formation proceeded much slower to give the low surface brightness, but as much dynamical evolution has occured as in the Galactic disk.

Since $V_{\rm max}^{\rm disk} = 70 \pm 15$ km/s, IC 5249 is *not* maximum disk. Using the ratio $h_{\rm R}/h_{\rm z}$ gives $V_{\rm max}^{\rm disk} = 72 \pm 25$ km/s.