THE STARS AND GAS IN OUTER PARTS OF GALAXY DISKS

EXTENDED OR TRUNCATED – FLAT OR WARPED?

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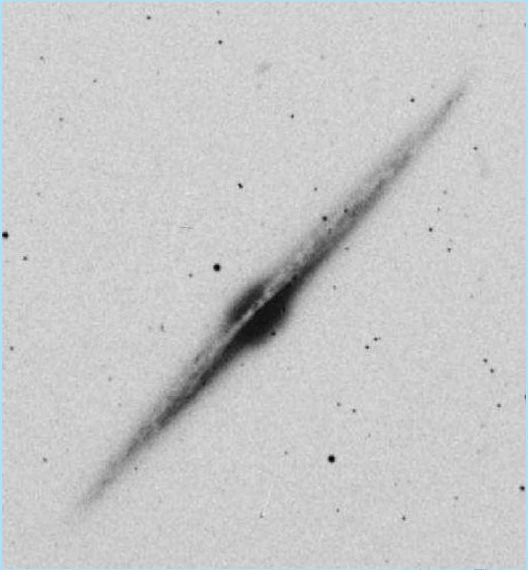
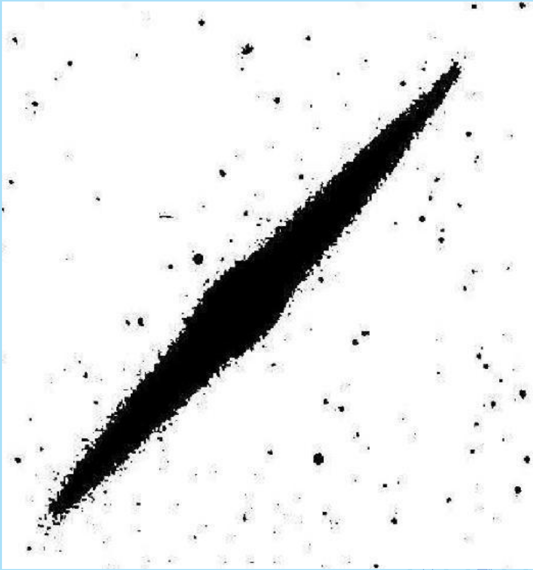
Truncations in edge-on galaxies

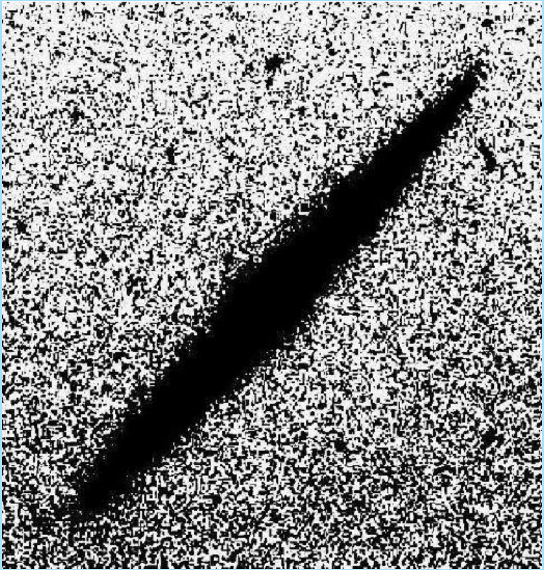
Observations of truncations

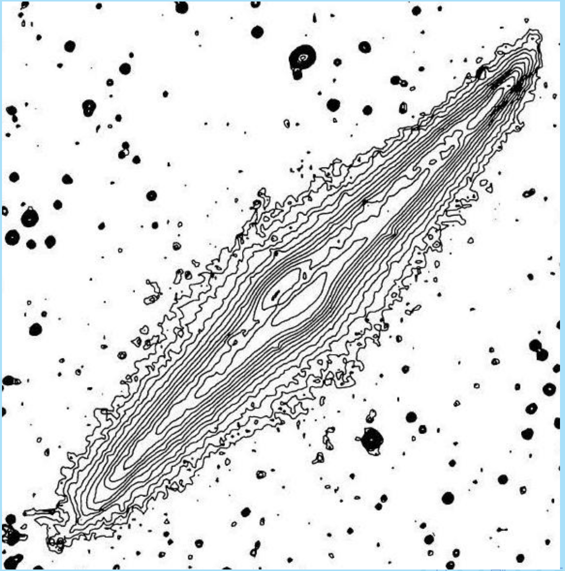
- In edge-on spiral galaxies it was noted[1] that the radial extent did not grow with deeper and deeper photographic exposures.
- Especially when a bulge was present, in contrast the minor axis did grow considerably with deeper images.
- A prime example of this phenomenon of these disk truncations is the galaxy NGC 4565.

[1] van der Kruit, A.&A.Suppl. 38, 15 (1979)

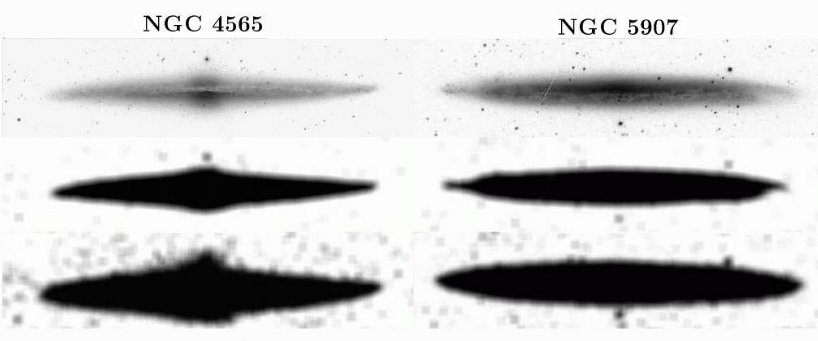






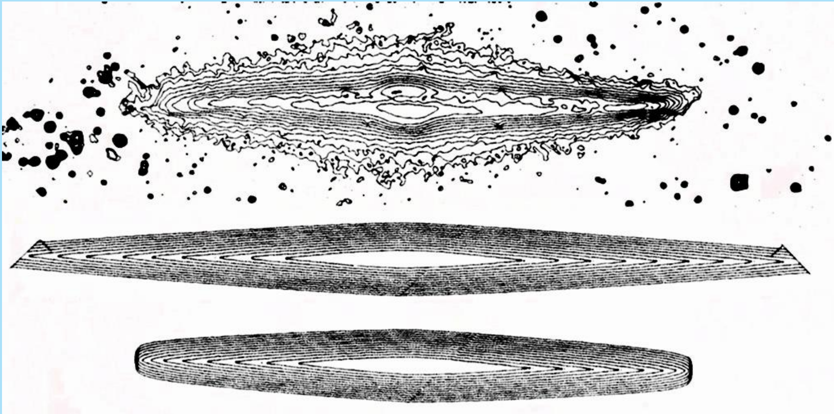


NGC 4565 and NGC 5907 in one diagram[2].

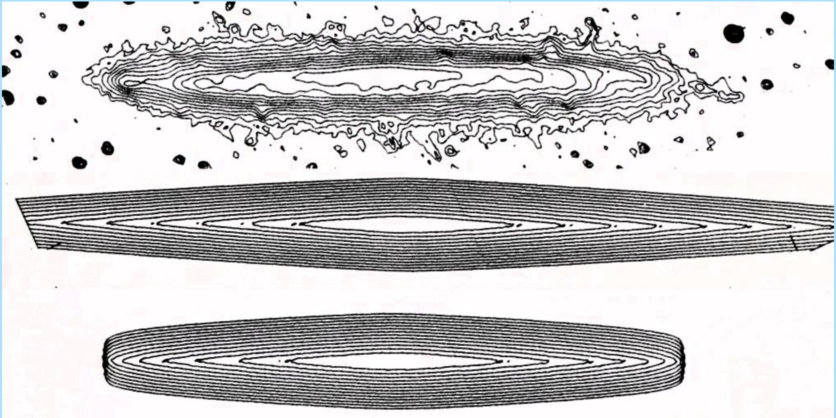


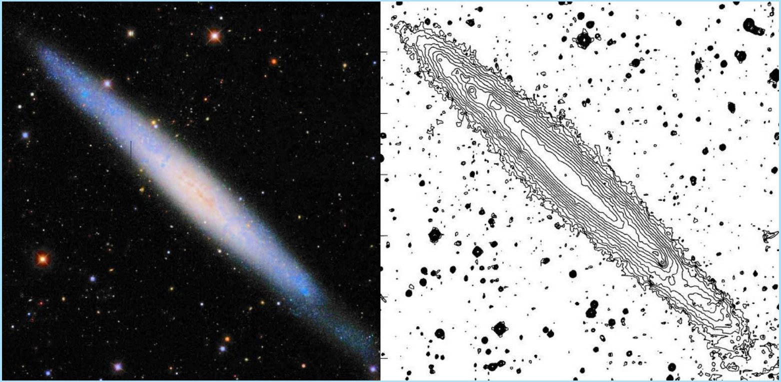
[2]From van der Kruit, A.&A. 466, 883 (2007)

Contours for NGC 4565 compared to an infinite disk and one with a infinitely sharp truncation.



Contours for NGC 5907 compared to an infinite disk and one with a infinitely sharp truncation.

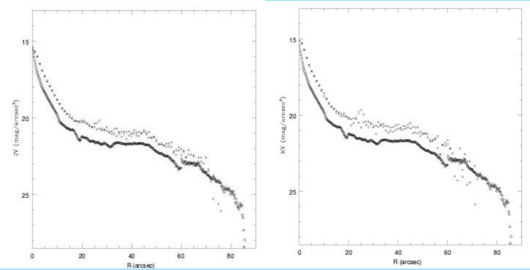




Faint HST starcounts[3] have confirmed the presence of the truncation in NGC 4244.

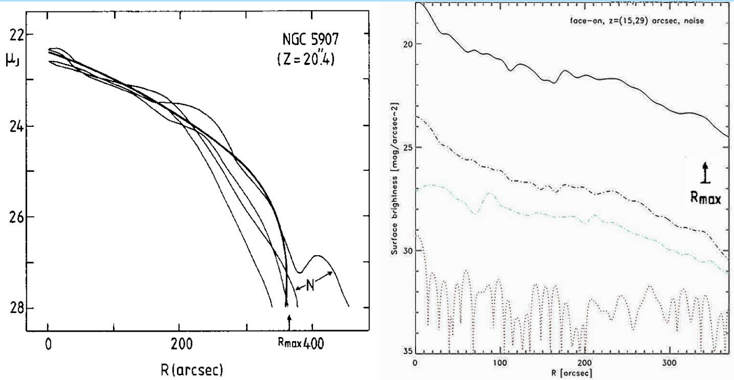
[3] de Jong et al., Ap.J. 667, L49 (2007)

- Van der Kruit & Searle (1981a) state in their abstract: *"This cut-off is very sharp with an e-folding of less than about 1 kpc"*, based on spacing of the outer isophotes.
- Very sharp profiles are actually obtained[4] after deprojections of near-IR observations in edge-on galaxies.



[4] Florido et. al., A.& A. 378, 82 (2001), 455, 467 (2006) and 472, L39 (2007)

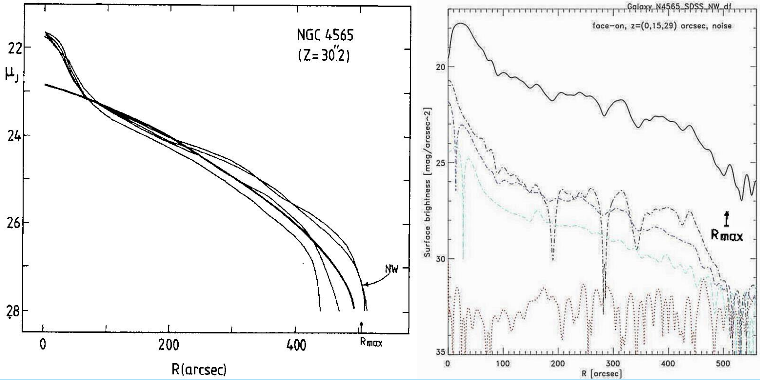
Michael Pohlen kindly made deprojections using SDSS-data, following his recent procedure[5]. Here is NGC 5907.



The deprojection is done on the quadrant of the lower 'N'-profile.

[5]Pohlen, Zaroubi, Peletier & Dettmar, MNRAS 378, 594 (2007)

In NGC 4565 the deprojection is done on the 'NW'-side.



The outer slope (which sets in somewhat before $R_{\rm max}$) is about 1.5 kpc in scalelength.

Models for the origin of truncations

I. The truncations are the current extent of slowly growing disks (from the inside to the outside) from accretion of external material[6].

- This model predicts substantial age changes across disks, which are not observed[7].
- Furthermore, current thinking is that disks formed either in an early monolythic collapse or by a slower process of merging of smaller systems in a hierarchical formation picture.

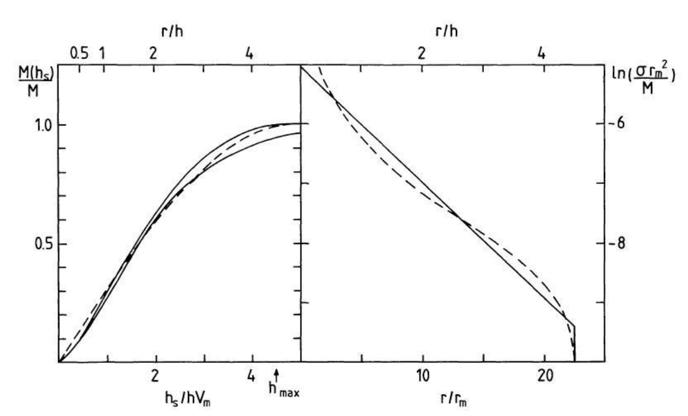
[6] Larson, MNRAS 176, 31 (1976)
[7] de Jong, A.&A. 313, 377 (1996)

II. Inhibition of star formation when the gas surface density falls below some threshold (surface) density for local instability[8].

- The Goldreich-Lynden-Bell criterion for stability of a gaseous layer gives a poor prediction for the truncation radii[9].
- Another problem is that observations of the rotation curves of a some galaxies (e.g. NGC 5907 and NGC 4013[10]) show features near the truncations that indicate that the **mass** distributions are also truncated.
- Schaye predicts an anti-correlation between $R_{\rm max}/h$ and h, which is not observed (see later).

[8] Fall & Efstathiou, MNRAS 193, 189 (1980); Schaye, Ap.J. 609, 667 (2004)
[9] van der Kruit & Searle, A.&A. 110,61 (1982)
[10] Casertano, MNRAS 203, 735 (1983); Bottema, A.&A. 306, 345 (1996)

III. The truncation corresponds to a maximum in the specific angular momentum in the protogalaxy[11].



[11] van der Kruit, A.&A. 173, 59 (1987)

- If the collapse occurs from a Mestel sphere[12] (that has uniform density and angular velocity) with detailed conservation of specific angular momentum[13] in the force field of a dark halo with a flat rotation curve, a roughly exponential disk results with a cut-off at about 4.5 scalelengths.
- This provides both an explanantion for the exponential nature of disk as for the occurence of the truncations.
- However, it is not unlikely that some redistribution of angular momentum due to bars, etc. occurs.

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[12] Mestel, MNRAS 126, 553 (1963)
[13] Fall & Efstathiou, *op. cit.*

IV.

It is also possible that substantial redistribution of angular momentum takes place, such that it is unrelated to the initial distribution in the material that formed the disks.

- Bars may play an important role in this, as suggested by Erwin et al.[14].
- In fact a range of possible agents, such as bars, density waves, heating and stripping of stars by bombardment of dark matter subhalos, has been invoked[15].

[14] Erwin, Pohlen, Beckman, Gutiérrez & Aladro, Astro-ph 0706.38291 (2007)

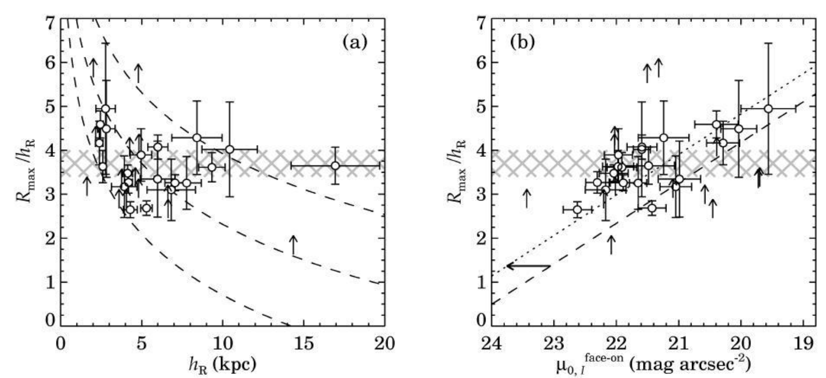
[15] de Jong, Seth, Radburn, Bell, Brown, Bullock, Courteau, Dalcanton, Ferguson, Goudfrooij, Holfeltz, Holwerda, Purcell, Sick & Sucker, Ap.J. 667, L49 (2007)

V. The magnetic model[16], in which a magnetic force breaks down as a result of star formation so that stars escape.

The evidence for the presence of sufficiently strong magnetic fields needs further strengthening.

[16] Battener et al. A.&A. 338, 313 (2002), Florido et al. A.&A. 455, 475 (2006)

Below are the correlations of cut-off radius $R_{\rm max}$ in terms of exponential scalelengths h with h itself and with the face-on central surface brightness $\mu_{\circ,\rm fo}$.[17]



[17] Kregel & van der Kruit, *op. cit.*

- The property $R_{\max}/h$ does not depend strongly on h, but is somewhat less than the 4.5 predicted from the collapse from a simple Mestel-sphere.
- There is some correlation between $R_{\max}/h$ and $\mu_{\circ,\mathrm{fo}}$, indicating approximate constant disk surface density at the truncations, as predicted by the star-formation theshold model.
- The star-formation threshold model predicts an anti-correlation between $R_{\max}/h$ and h, which is not observed.
- The maximum angular momentum hypothesis does not predict that $R_{\max}/h$ depends on h or $\mu_{\circ,\mathrm{fo}}$ and it therefore requires some redistribution of angular momentum in the collapse.

Conclusions

- Many, but not all, edge-on stellar disks in galaxies show relatively sharp truncations in their radial distributions.
- The model with a threshold in star formation as the origin of the truncations is not in agreement with the observed distribution of $R_{\max}/h$ with h.
- If the truncation radius corresponds to a maximum in the specific angular momentum distribution that existed already before the collapse and that is conserved through the collapse, the initial configuration is either not identical to that of a Mestel sphere and/or the conservation of specific angular momentum is not perfect.

Truncations in moderately inclined galaxies

General considerations

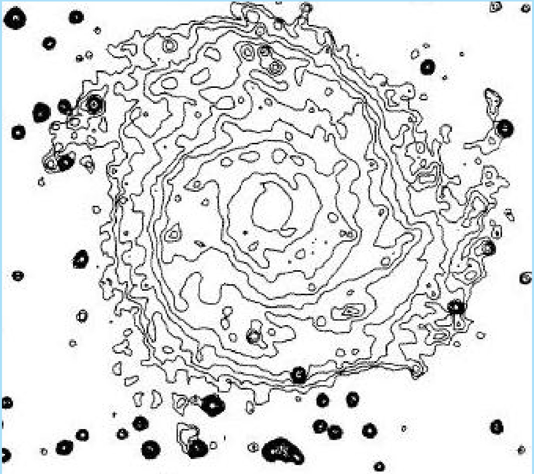
Due to line-of-sight integration truncations should more difficult to detect in face-on galaxies than in edge-on ones.

The expected surface brightness at 4 scalelengths is about 26 B-mag arcsec^{-2} or close to sky.

Also one has to be aware of azimuthal averaging. A good example for illustration is NGC 628.[18]

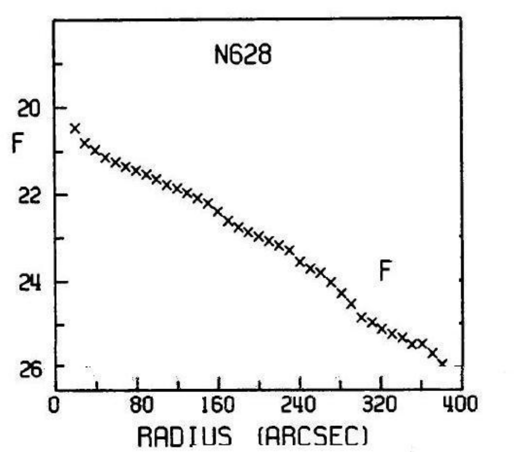
[18] Wevers, van der Kruit & Allen, A.&A.Suppl. 66, 505 (1986), van der Kruit, A.&A. 192,117 (1988)

The isophote map shows that the outer contours have a much smaller spacing than the inner ones.

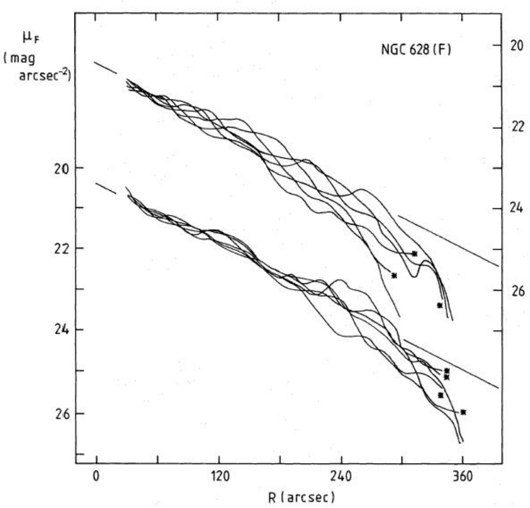


The usual procedure is to derive the inclination and major axis from kinematics and then proceed to make an azimuthally averaged radial surface brightness profile.

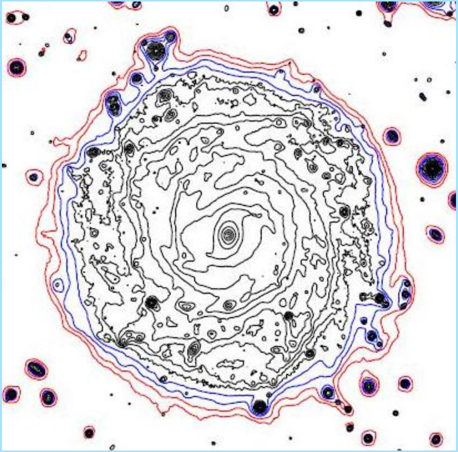
This smoothes out the sharp decline.



It can be recoverd by averaging in smaller sectors.



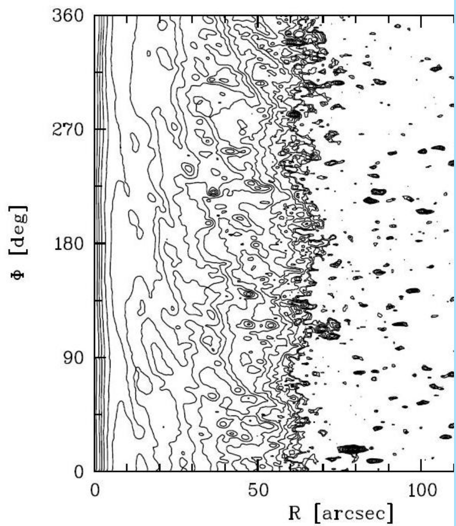
The effects is seen here as well in the red and blue contours of NGC 5923.[19]



[19] Pohlen, Dettmar, Lütticke & Aronica, A.&A. 392, 807 (2002)

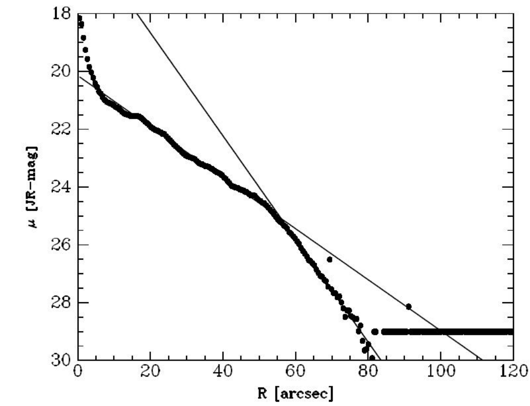
Here is the same data in polar coordinates.

The irregular outline shows that some smoothing out will occur contrary to observations in edge-on systems.



There is in this radial profile clear evidence for a change in slope, but less steep than the spacing of the isophotes indicated.

So we will always find a sharper truncation in “face-on” than in edge-on systems.



The work of Pohlen and collaborators

Extensive work has been performed by Michael Pohlen and collaborators.

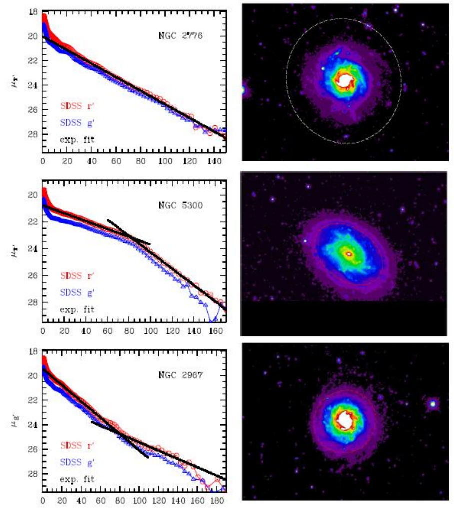
- A sample of moderately inclined systems[20] has been studied through ellipse-fitting of isophotes in SDSS data.
- A few edge-on systems[21] have been studied using a decomposition thecnique.

[20] Pohlen & Trujillo, A.&A. 454, 759 (2006)
[21] Pohlen, Zaroubi, Peletier & Dettmar, MNRAS 378, 594 (2007)

Pohlen & Trujillo distinguish three types of truncations:

- Type I: no break
- Type II: downbending break
- Type III: upbending break

There are subtypes, of which the indication CT for Classical Truncation is important to follow.



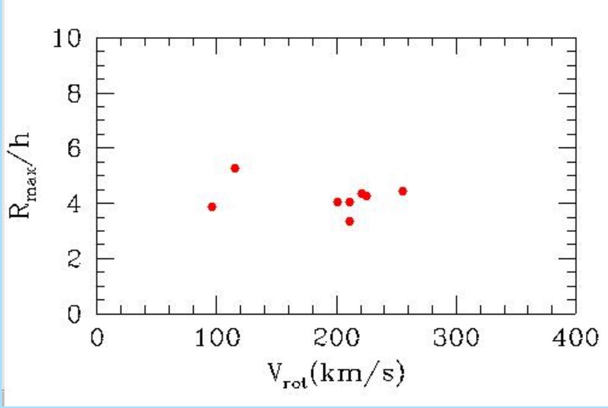
In the literature there are the following samples in the optical:

authors	orient.	trunc.	no trunc.	up-bend.
vdK & Searle (1981/2)	edge-on	8	–	–
Pohlen et al. (2000)	edge-on	30	–	–
Pohlen et al. (2002)	face-on	3	–	–
Kregel et al. (2002)	edge-on	20	11	–
Pohlen & Trujillo (2006)	inclined	54	9	21
vdK (2007)	edge-on	19	7	–
Pohlen et al. (2007)	edge-on	9	1	1

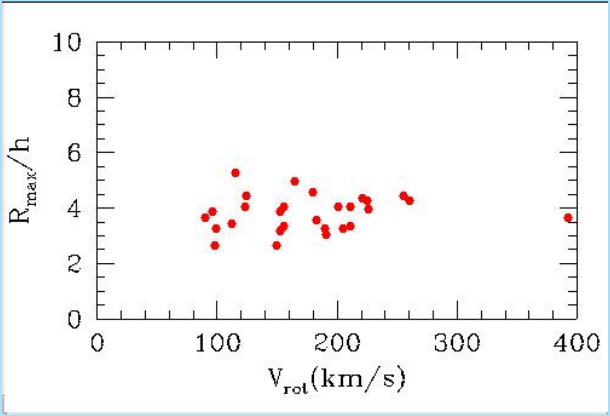
For almost all of these the rotation velocity can be found using HYPERLEDA.

First look at the ratio $R_{\rm max}/h$ as a function of $V_{\rm rot}$, both of which are distance independent.

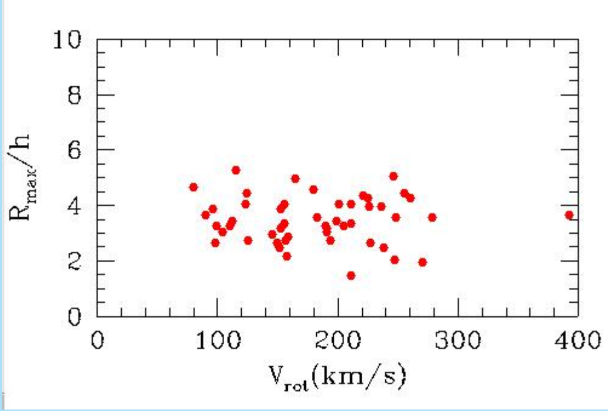
We start with the sample of van der Kruit & Searle (1981, 1982).



Then I add the data of Kregel, van der Kruit & de Grijs (2002).

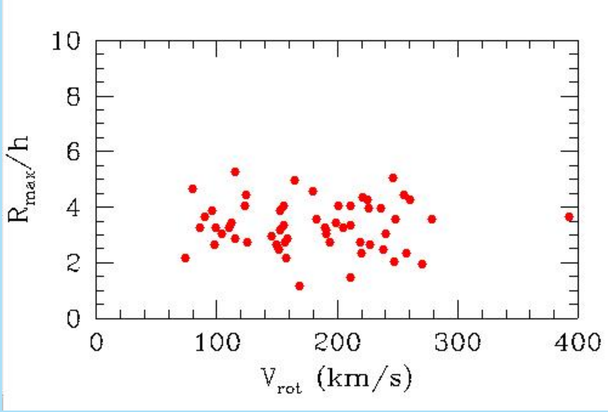


Here the data in Pohlen, Dettmar, Lütticke & Schwarz- kopf (2000) have been added.



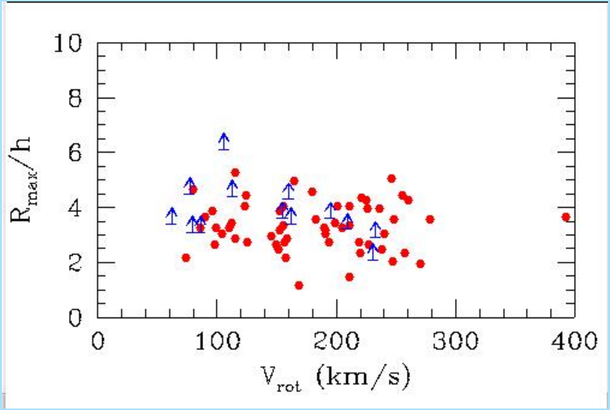
And here the data of Pohlen, Zaroubi, Peletier & Dettmar (2007).

This is the full data set for edge-on galaxies.

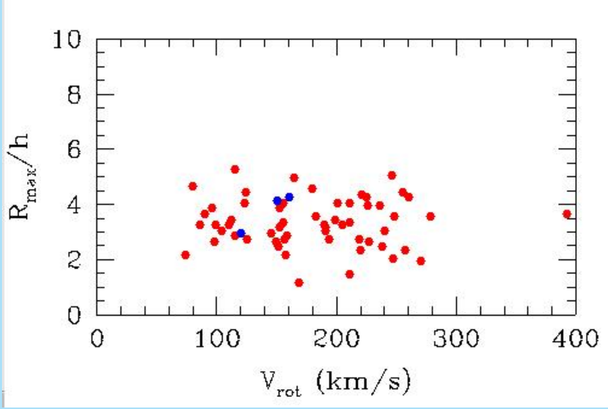


I here also added the lower limits.

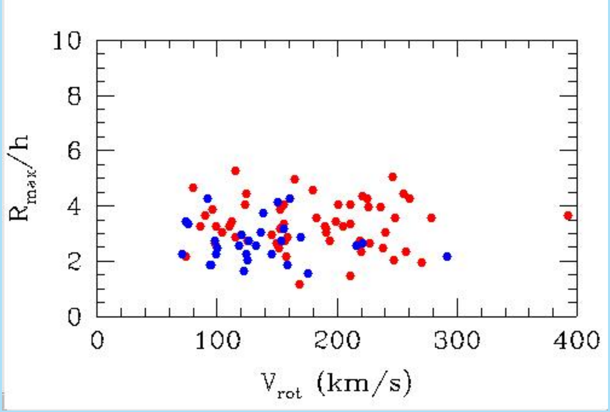
I will not include these further, but notice that they not yet make the distribution broader.



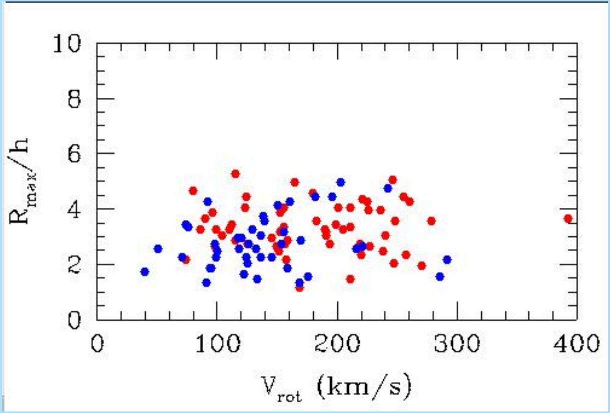
Here the three face-on galaxies in Pohlen, Dettmar, Lütticke & Aronica (2002) have been added.



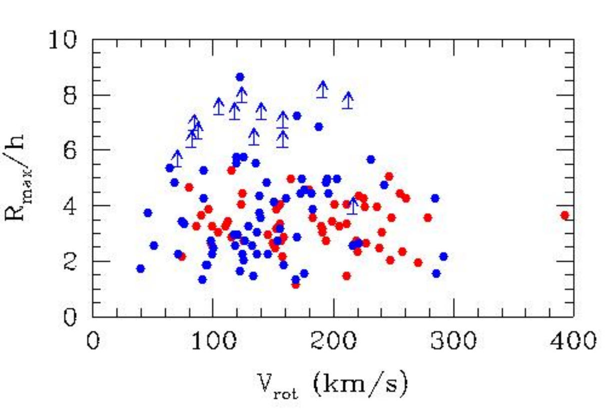
Now I add the galaxies that have been classified Type II-CT (Classical Truncation) in the moderately inclined sample of Pohlen & Trujillo (2006).



Here I add the rest of the galaxies of Type II of Pohlen & Trujillo.



Here I add the galaxies of Type III and Type I; the latter are lower limits correspon-ding to the measured extent in the paper.



I conclude:

- The edge-on samples agree reasonably well among each other and there is no strong dependence of $R_{\max}/h$ on $V_{\rm rot}$.
- At least for the galaxies of the face-on Type II the distribution is similar as that for edge-on galaxies.

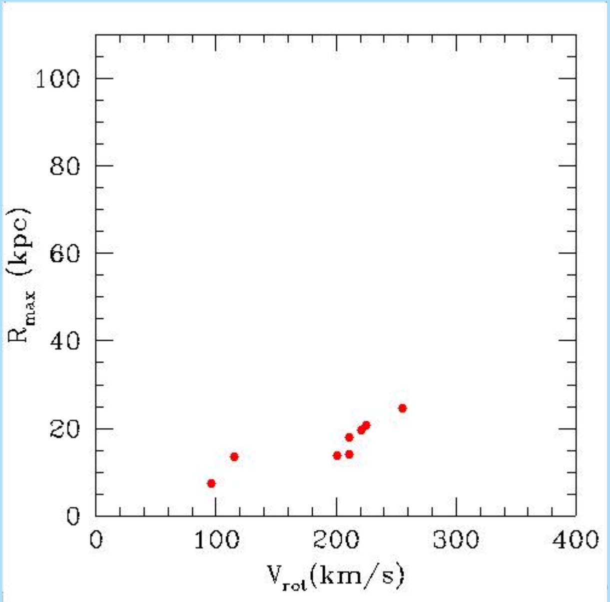
$R_{\rm max}$ versus $V_{\rm rot}$ and $R_{\rm max}/h$ versus h

We look at the correlation between the truncation radius $R_{\rm max}$ and the rotation velocity $R_{\rm rot}$

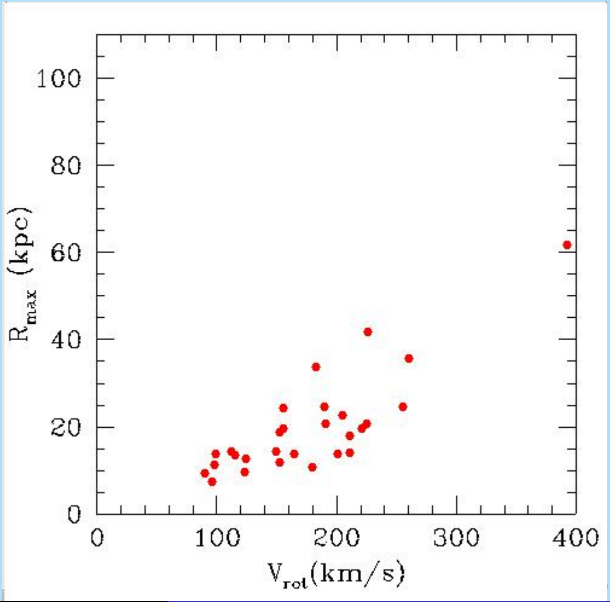
We will do this first for edge-on galaxies and then compare that to the sample of moderately inclined galaxies that has been presented by Pohlen & Trujillo (2006)

Here is first the data from various edge-on samples.

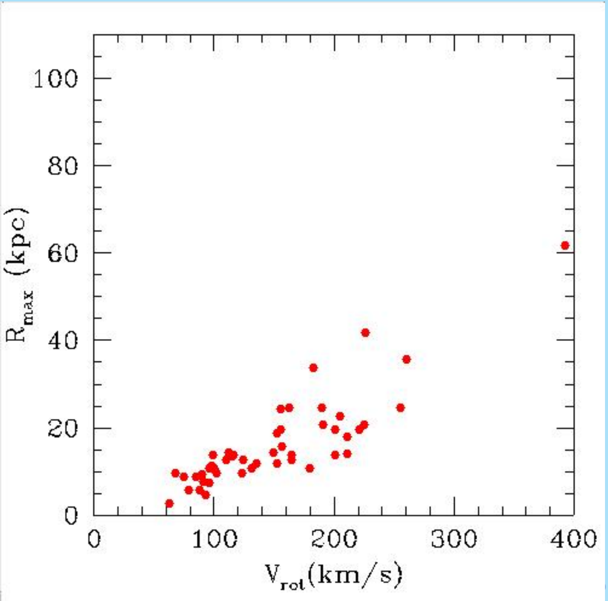
The data from van der Kruit & Searle (1981, 1982).



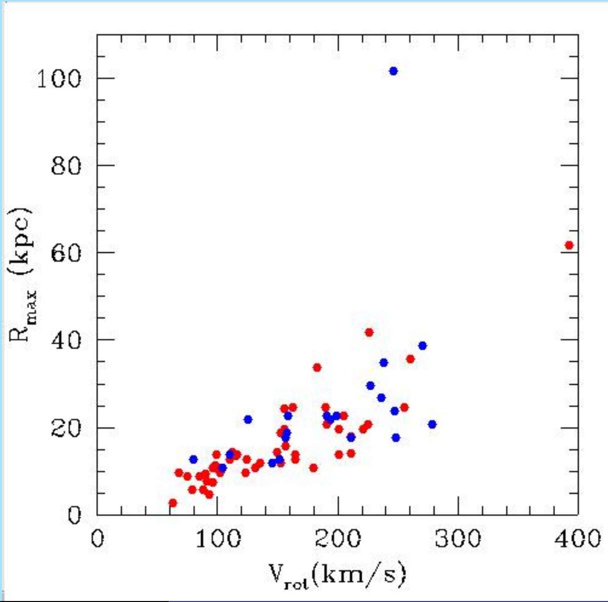
Add the data from Kregel, van der Kruit & de Grijs (2002).



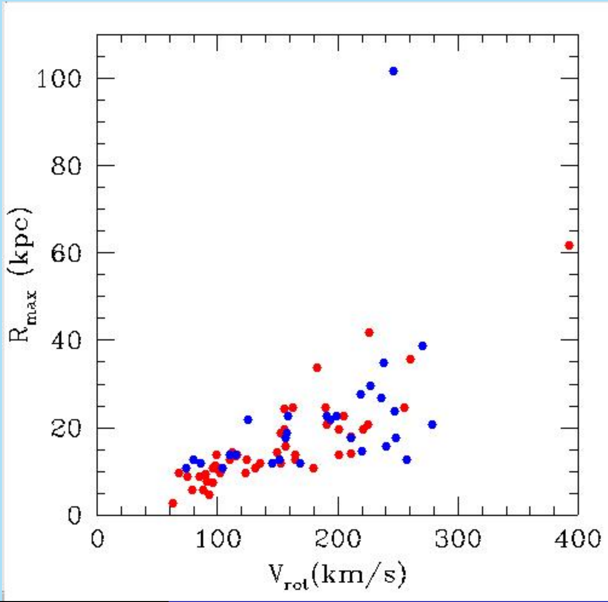
Add the data from van der Kruit (2007).



Add the data from Pohlen, Dettmar, Lütticke & Schwarzkopf (2002).

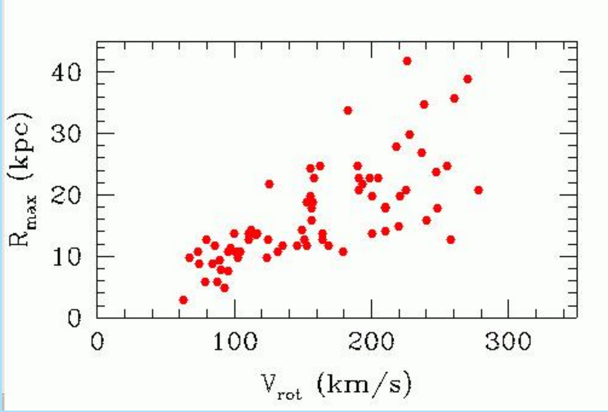


Add the data from Pohlen, Zaroubi, Peletier & Dettmar (2007).



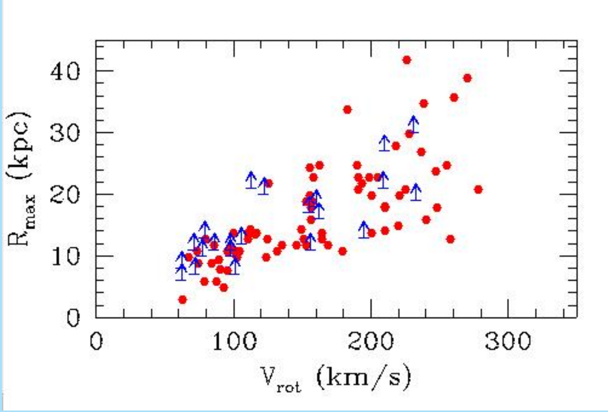
All the data on edge-on galaxies thus gives a reasonably well-defined correlation.

For the following I will leave out the two very high points.



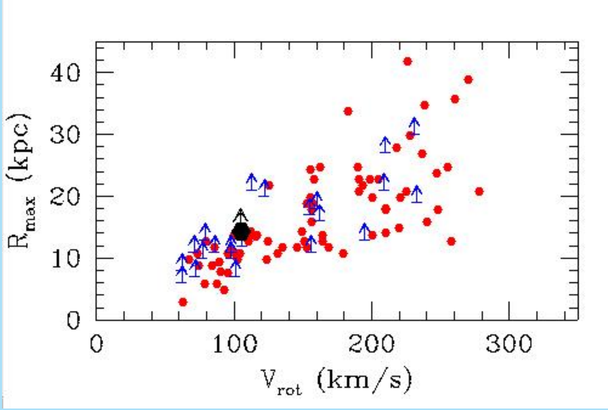
Now include the lower limits to the truncation radius from the same samples.

This does not change the picture much.



For the interest I add the point for NGC 300[22].

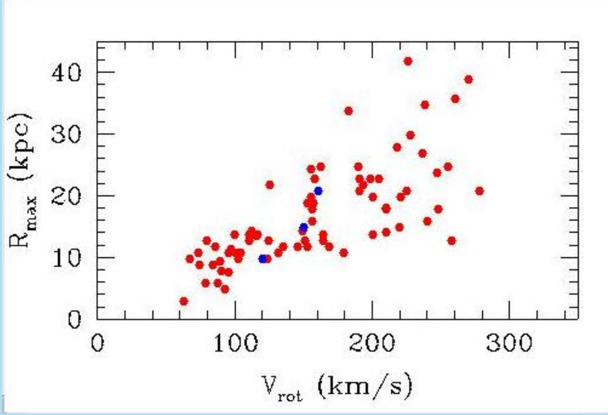
Although this disk extends to at least 10 scalelength it is still not outside the distribution observed in edge-on systems.



[22] Bland-Hawthorn et al., Ap.J. 629, 249 (2005)

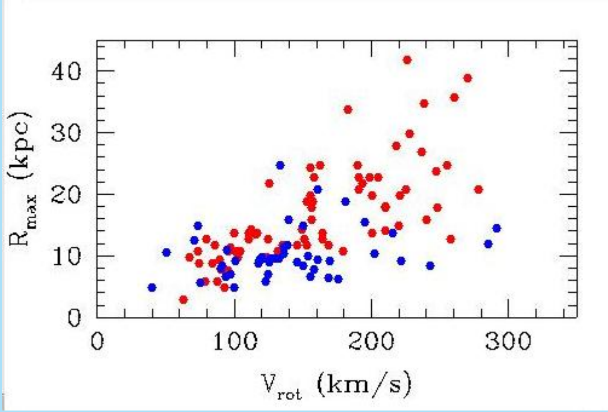
Now we will add data from samples of moderately inclined galaxies.

Here are the three points from Pohlen, Dettmar, Lütticke & Aronica (2002)



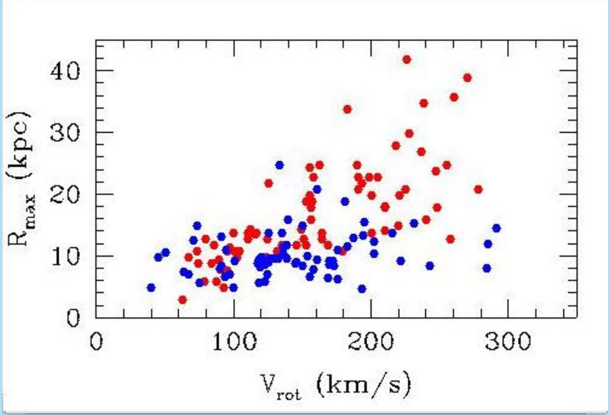
Nest we add the data from the sample of Pohlen & Trujillo (2006).

First the galaxies with truncation Type II (“down-bending break”).

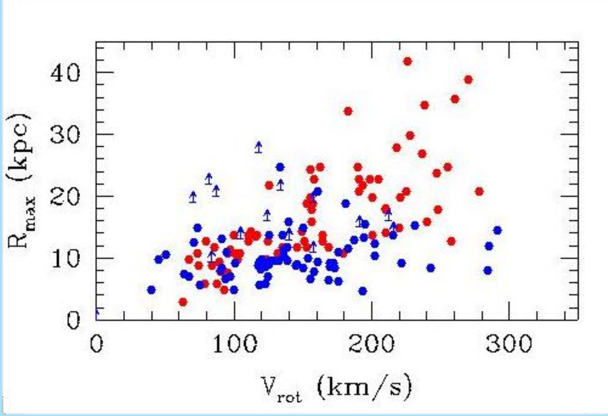


This indicates a different distribution.

Add also the data for galaxies of Type III ("upbending break").

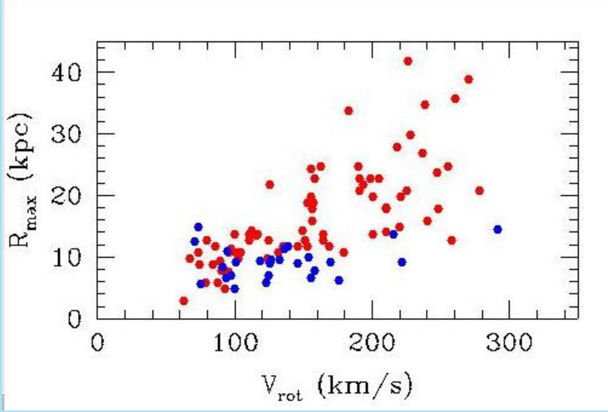


Finally here are also included the data for the sample of Type I ("no break").



Restrict the points now only to the galaxies with break Type II-CT ("classical truncation").

Still we see that the two samples have different distributions.



The face-on sample of Pohlen & Trujillo shows smaller $R_{\rm max}$, which may actually be expected from their method.

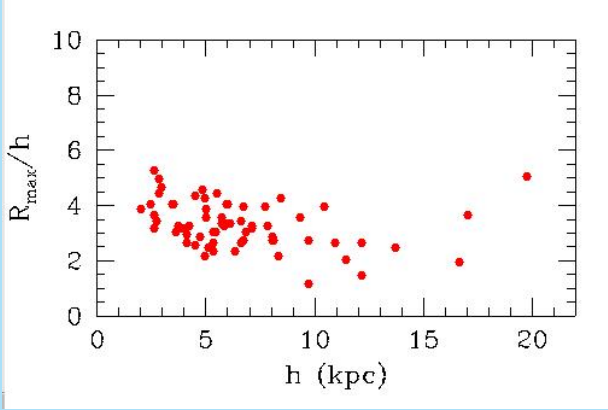
But it also shows no correlation of $R_{\rm max}$ with $V_{\rm rot}$, which gives a clear relation in edge-on systems.

So:
Are we in the case of truncations in edge-on galaxies and in moderately inclined ones looking at the same thing?

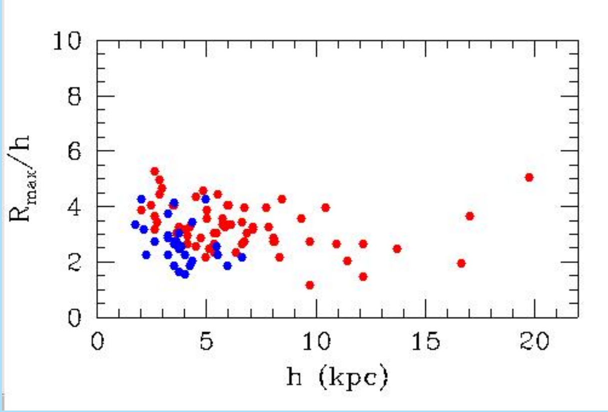
We may also look at $R_{\max}/h$ versus h.

Here is the data for all edge-on galaxies.

Note the absence of the anti-correlation predicted by Schaye.

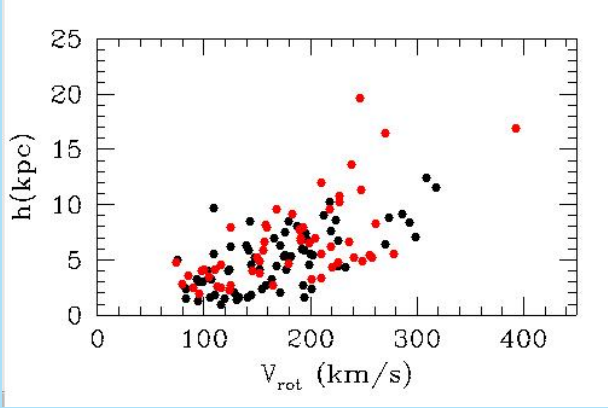


And here I have added the Type II CR data from Pohlen and Trujillo.

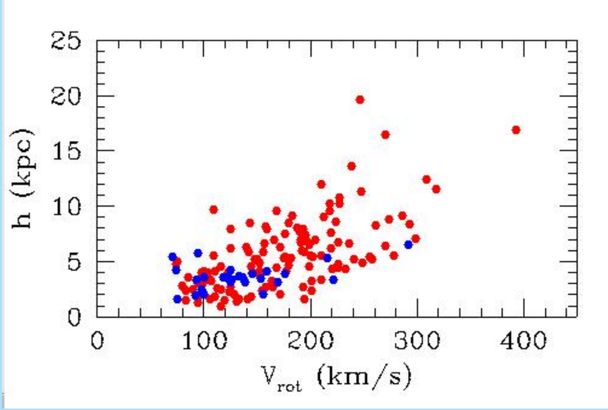


Look now at h versus $V_{\rm rot}$, which is a well-known scaling relation for spirals.

The red dots are the complete edge-on sample and the black dots are the sample of Roelof de Jong's thesis.

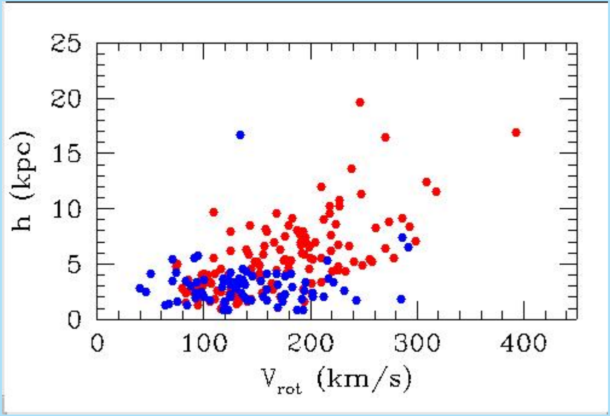


Now make the de Jong points also red and compare with the Pohlen & Trujillo sample of Type II-CT.



And here with the full Pohlen & Trujillo sample.

The blue points do not show the expected relation.



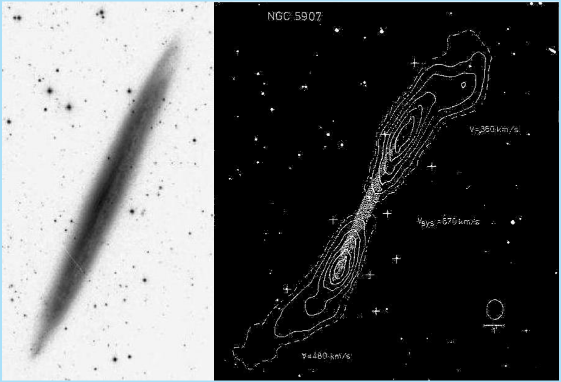
Conclusions

- Measurements of truncations in edge-on and face-on systems has fundamental differences.
- It is not clear that in the study of truncations in face-on systems by Pohlen & Trujillo (2006) one is consistently measuring the same feature as in edge-on galaxies.
- In particular the lack of a correlation of truncation radius (and scalelength) with rotation velocity (which is well established for edge-on galaxies) needs clarification on whether this is due to effects of sample selection or the deprojection method.
- In this area there clearly is need for further work.

Truncations and warps

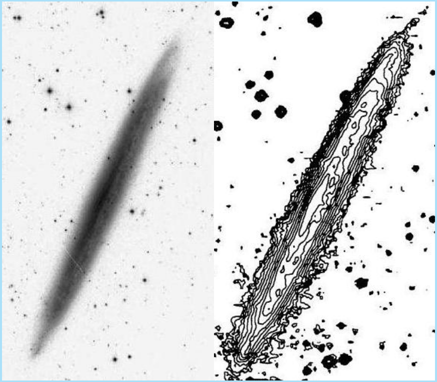
Observations of HI-warps

- Warps in the HI in external galaxies are most readily observed in edge-on systems as NGC 5907[23].



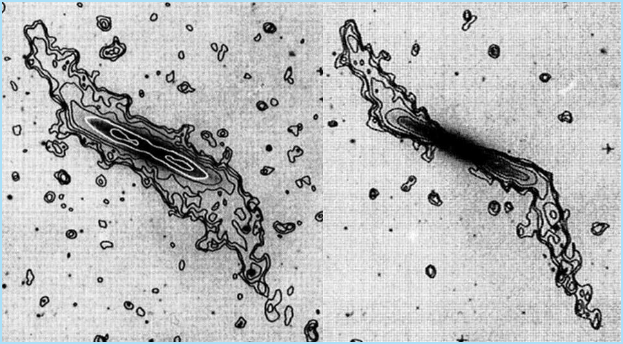
[23] Sancisi, A.&A. 74, 73 (1976)

- It is interesting to note that NGC 5907 has a clear and sharp truncation[24] in its stellar disk at the radius, where also the warp starts.



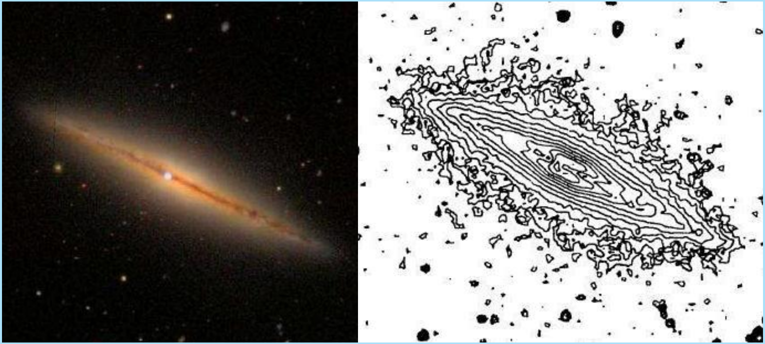
[24] P. C. van der Kruit & L. Searle, *op. cit.*

- An extreme example is the "prodigious warp" in NGC 4013[25].
- This warp is very symmetric and starts suddenly near the end of the optical disk (see the extreme channel maps on the right).



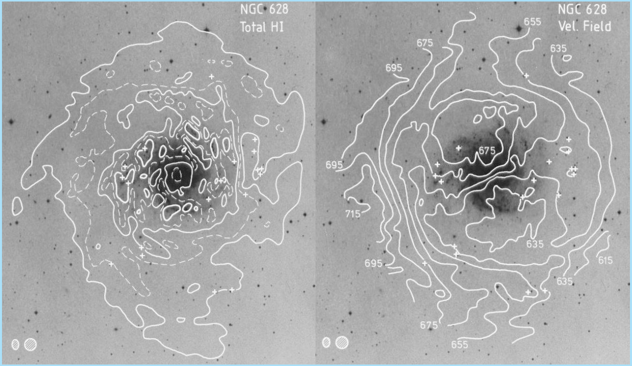
[25] Bottema, Shostak & van der Kruit, Nature 328, 401 (1987); Bottema, A.&A. 295, 605 (1995) and 306, 345 (1996)

- NGC 4013 also has a clear truncation[26] in its stellar disk. The three-dimensional analysis[27] does confirm that in deprojection the warp starts very close to the truncation radius.



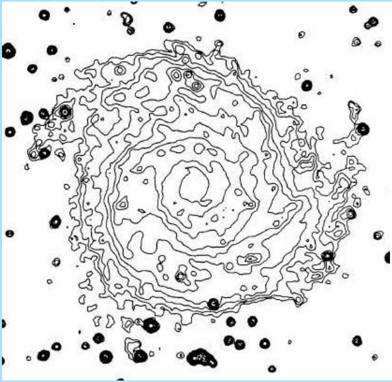
[26] van der Kruit & Searle, *op. cit.*
[27] Bottema, *op. cit.*

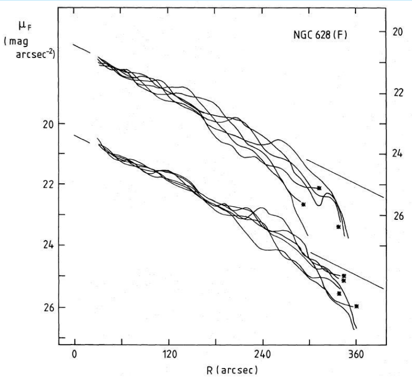
- NGC 628 is almost completely face-on.
- The HI-velocity field shows a complecated pattern, that shows that in the tilted-ring model the rings actually go through the plane of the sky[28].



[28] Shostak & van der Kruit, A.&A. 132, 20 (1984)

- The radial luminosity profiles[29] show evidence for a truncation.
- This truncation coincides with the onset of the warp.





[29]Shostak & van der Kruit, *op. cit.*; van der Kruit, A.&A. 192, 117 (1988)

The residual HI-velocity field after subtraction of that of the rotation shows no systematic pattern and has an r.m.s. of only 4 km/s, so that the HI-layer must be extremely flat[30].

So:

- Stellar disks are very flat (except maybe near the edges where small optical warps are found).
- HI-warps often start suddenly at about the truncation radius of the stellar disk.

So, I will in this section further investigate the relation between truncations and HI-warps in edge-on galaxies.

[30] Shostak & van der Kruit, op. cit.

Truncations in the García-Ruiz et al. sample

- Inigo García-Ruiz[31] presented HI observations of a sample of edge-on galaxies ("Hunting for warps").
- His sample consisted of 26 edge-on galaxies in WHISP[32].
- At least 20 show evidence for an HI warp.
- Unfortunately, the optical surface photometry could not be calibrated.

[31] Ph.D. Thesis, University of Groniongen (2001); see also García-Ruiz, Sancisi & Kuijken, A.&A. 394, 796 (2002)

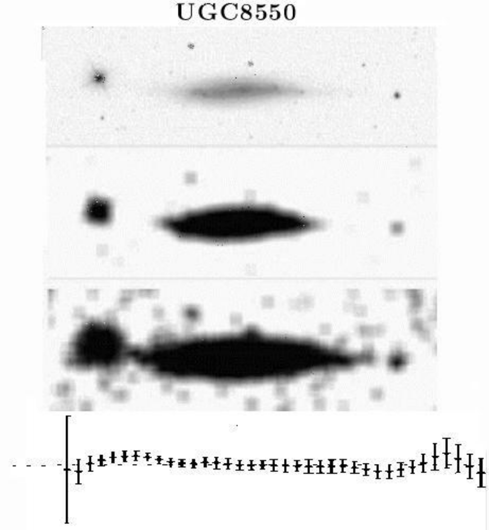
[32] Westerbork observations of neutral Hydrogen in Irregular and SPiral galaxies; www.astro.rug.nl/whisp/.

- In a recent paper[33] I investigated whether the Sloan Digital Sky Survey (SDSS) or other digital sky surveys van be used to see if there are truncations and
- if so, where the warps start w.r.t. to these.

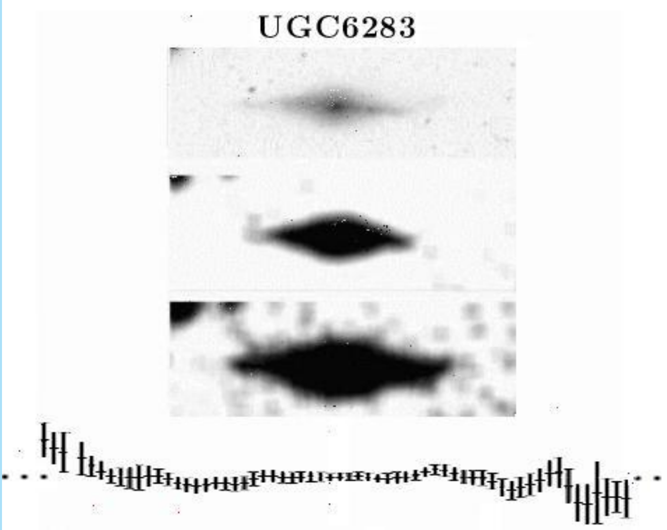
Here are a few examples.

[33] van der Kruit, A.&A. 466, 883 (2007)

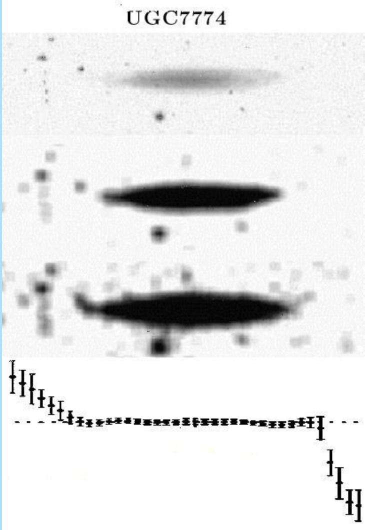
UGC 8550: No truncation and no warp



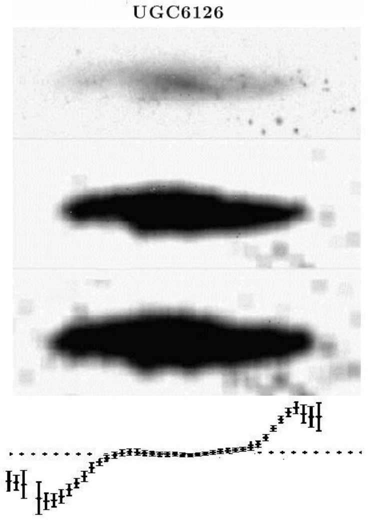
UGC 6283: No truncation, warp at larger radius.



UGC 7774: Truncation and a warp starting at R_{max}.



UGC 6126: Truncation and a warp starting at a radius $< R_{max}$.



The observed distribution of the ratio R_{warp}/R_{max} and that for a random distribution of viewing angles for three values of the "real" ratio (p from Kolmogorov-Smirnov).

$\frac{R_{warp}}{R_{max}}$	#	$R_{warp} = 1.0R_{max}$	$R_{warp} = 1.1R_{max}$	$R_{warp} = 1.2R_{max}$
1.2	1	–	–	3.3
1.1	2	–	3.5	2.5
1.0	2	3.6	2.6	1.7
0.9	3	2.7	1.8	1.4
0.8	2	1.9	1.5	1.3
0.7	2	1.6	1.4	1.2
–	6	8.1	7.2	6.6
p		0.706	0.963	0.538

The observations are most consistent with the situation, where all warps star at about 1.1 R_{max}.

Systematics of HI-warps

- Briggs[34] formulated a set of rules of behaviour for HI- warps.

RULES OF BEHAVIOR FOR GALACTIC WARPS

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ABSTRACT

A sample of galaxies is now available for which H I 21 cm line observations allow the development of detailed kinematic models based on concentric, circular rings with adjustable inclinations and orbital velocity. By examining these warped systems in a variety of reference frames, clear empirically determined "rules" for the behavior of galactic warps have emerged.

Analysis of 12 galaxies with extended, warped H I disks show the following:

1. The H I layer typically is planar within R_{25}, but warping becomes detectable within $R_{Ho} = R_{26.5}$. Warping within R_{Ho} appears consistent with a common (i.e., straight) line of the nodes (LON) measured in the plane defined by the innermost regions of the galaxies.

2. Warps change character at a transition radius near R_{Ho}.

3. For radii larger than R_{Ho}, the LON measured in the plane of the inner galaxy advances in the direction of galaxy rotation for successively larger radii. Thus, the nodes lie along leading spirals in this frame of reference.

4. The galaxy kinematics uniquely specify a new reference frame in which there is a common LON for oribits within the transition radius and also a *differently oriented* straight LON for the gas outside the transition radius. This new reference frame is typically inclined by less than 10° to the plane of the inner galaxy.

The lack of a common LON throughout the entire warped disk argues against models that rely on normal bending modes to maintain warp coherence at all radii. Instead, the emerging picture may require galaxy models with two distinct regimes. Behavior in the outer regime is consistent with models that have the LON regressing most rapidly for oribits that are in closest proximity to the flat, stellar disk. In the inner regime, the disk may be settling into a warped mode.

[34] Briggs, Ap.J. 352, 15 (1990)

Properties of warps, as based on many studies, can be summarized as follows:

- All galaxies with extended HI disks have warps.
- Many galaxies have relatively sharp truncations.
- In edge-on galaxies the HI warps sets in just beyond the truncation radius, for less inclined systems it sets in near the Holmberg radius.
- In many cases the rotation curve shows a feature that indicates that there is at the truncation radius also a sharp drop in mass surface density.
- The onset of the warp is abrupt and discontinuous and there is a steep slope in HI-surface density at this point.
- Inner disks are extremely flat (with at most minor optical warps) and the HI-warps define a single "new reference frame".

Conclusions

- The inner disk (mostly stars) and the warped outer disk (mostly HI) are distinct components.
- They probably have distinct formation histories and formed during different epochs.
- Inner disks form initially and settle as rigid, flat structures with well-defined boundaries.
- Warps result from later infall with a different orientation of the angular momentum.
- The often regular structure of the warps and Brigg's new reference frame may result from re-arranging the structure from individual infalling gas clouds by interactions with neighbours or with an intergalactic medium.

Conclusions

- Truncations are a common feature in edge-on stellar disks.
- The relation of truncations as observed in moderately inclined systems to those in edge-on galaxies needs further clarification, in particular the absence of a correlation of $R_{\rm max}$ with $V_{\rm rot}$ and h in the face-on sample.
- The origin of truncations is most likely related to a maximum in the specific angular momentum in the material that formed the stellar disks, but such a model does probably require some redistribution of angular momentum.

- Stellar disks and their accompanying gas-layers are very flat.
- HI-warps start just beyond the truncation radius and stellar disks and HI-warps appear to be distinct components.
- This suggests that inner disks form initially and settle as rigid, very flat structures, while HI-warps result from later infall of gas with a different orientation of angular momentum.