TRUNCATIONS IN STELLAR DISKS AND WARPS IN HI-LAYERS IN SPIRAL GALAXIES

Piet van der Kruit
Kapteyn Astronomical Institute
University of Groningen, the Netherlands
www.astro.rug.nl/∼vdkruit

China, September/October 2011

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- Observations of truncations
- Models for the origin of truncations
- Truncations in moderately inclined galaxies
- The work of Pohlen and collaborators

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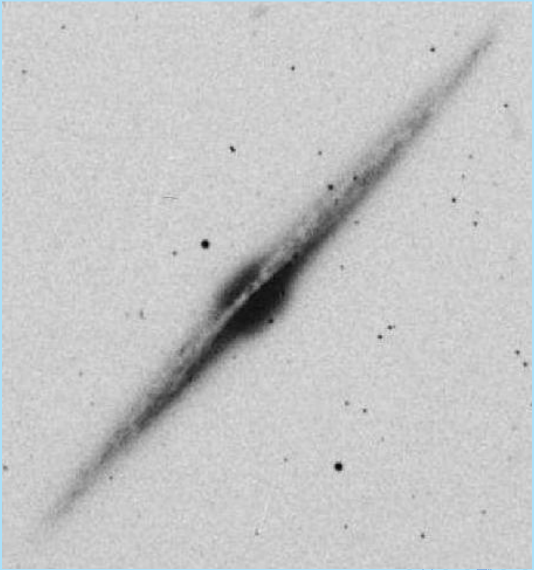
- Properties of warps
- Origin of warps
- Summary

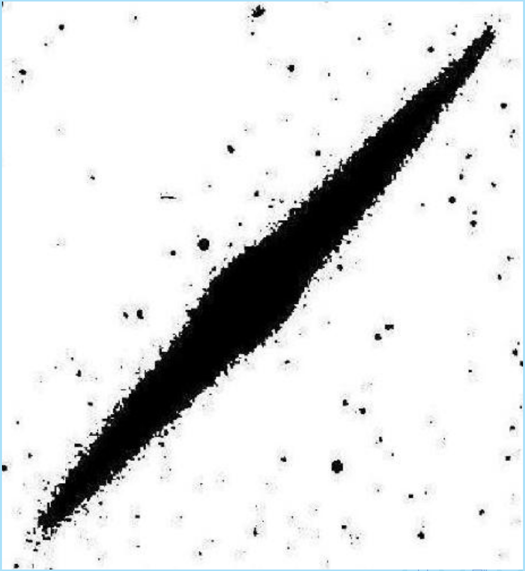
Truncations in stellar disks

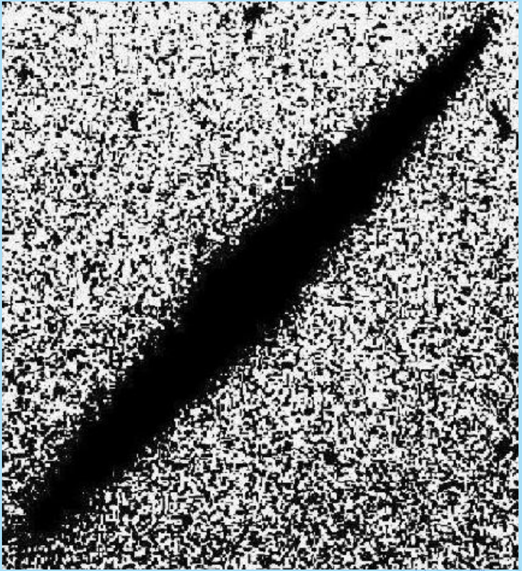
Observations of truncations

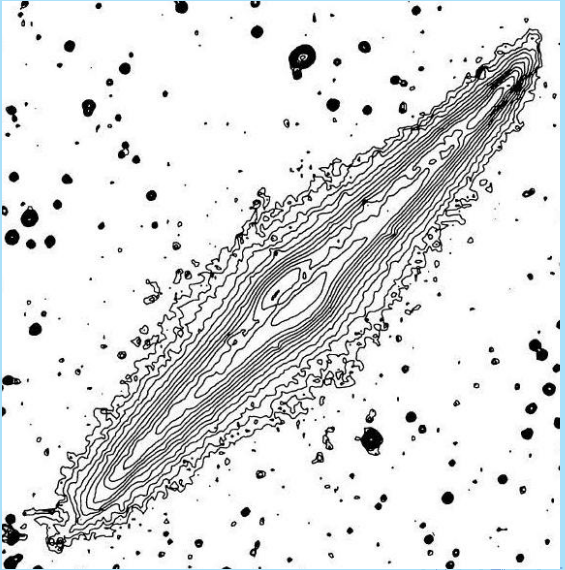
- In edge-on spiral galaxies it was noted[1] that the radial extent did not grow with deeper and deeper photographic exposures.
- Especially when a bulge was present the minor axis did grow with deeper images.
- A prime example of this phenomenon of so-called disk truncations is the galaxy NGC 4565.

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

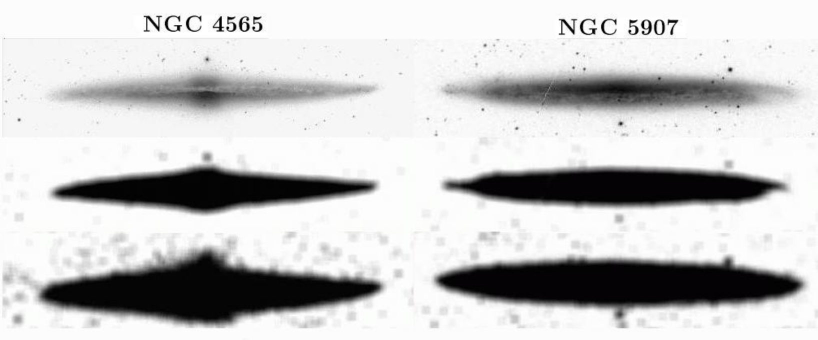








In one figure:



- Galaxy disk have a radial volume brightness distribution that is an exponential and the vertical one that of an isothermal sheet[2]:

$$L(R,z) = L_\circ \exp(-R/h)\,\mathrm{sech}^2(z/z_\circ) \quad \text{for} \quad R < R_{max}.$$

Disks have a constant thickness.

- Then the projected surface distribution (for R_{max} at infinity) will be

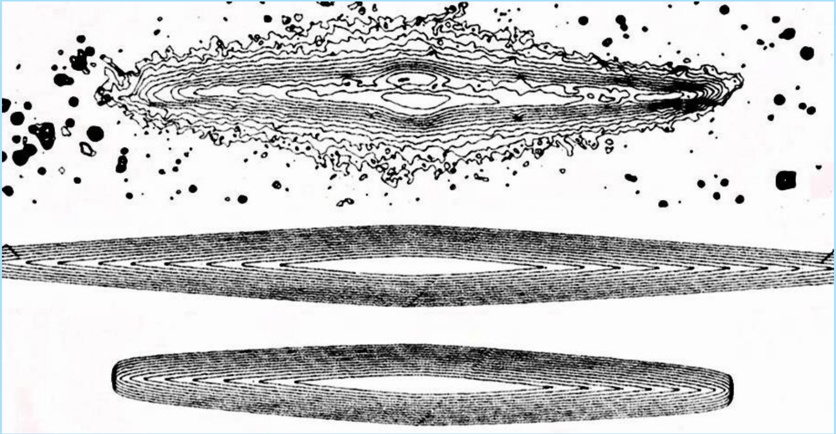
$$\mu(R,z) = 2hL_\circ(R/h)K_1(R/h)\,\mathrm{sech}^2(z/z_\circ),$$

where $K_1(R/h)$ is a Bessel function of the first kind, that approaches $\exp\,(-R/h)$ at large R.

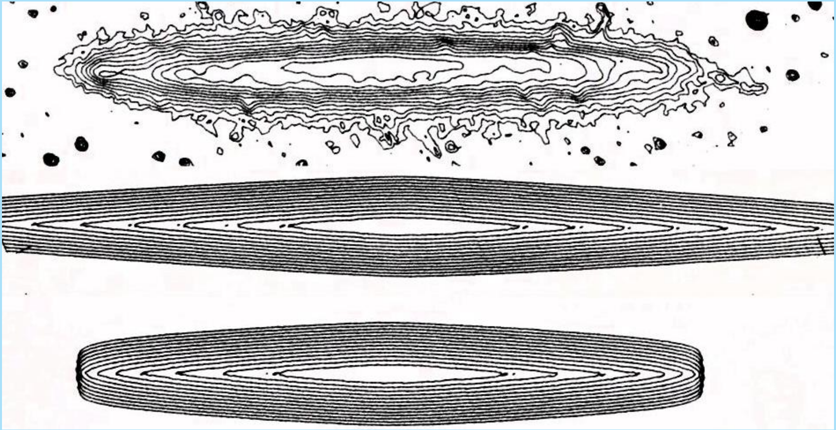
- For $R > R_{max}$, $\mu(R,z)$ drops quickly near R_{max}.

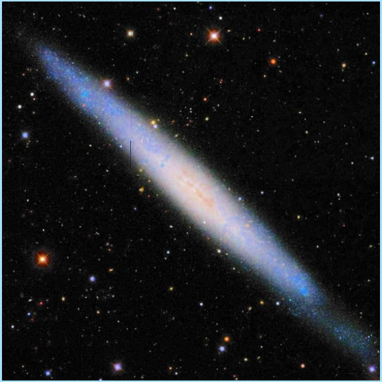
[2] P.C. van der Kruit & L. Searle, A.&A. 95, 105 (1981)

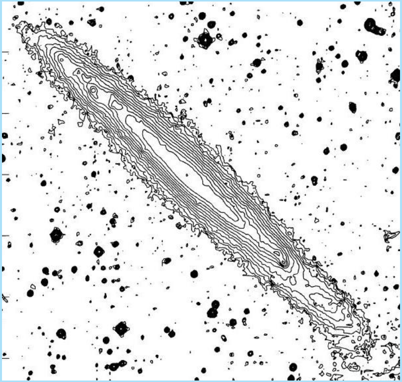
Contours for NGC 4565 compared to an infinite disk and one with a infinitely sharp truncation.



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



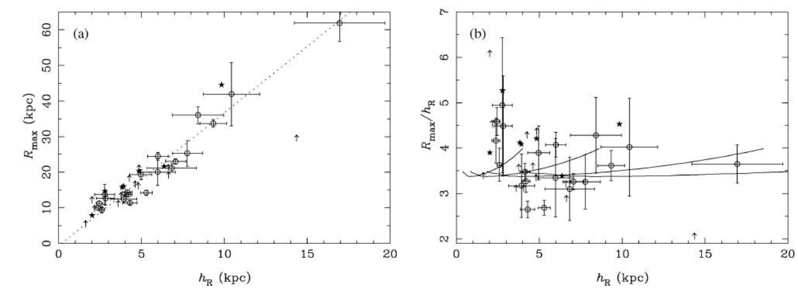




Faint HST starcounts[3] have confirmed the presence of the truncation in NGC 4244.

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

- More recent analyses[4] of a sample of 34 southern spiral galaxies shows that
  - At least 60% have radial truncations at a radius that we will call $R_{\rm max}$.
  - They occur on average at about 4 radial scalelengths h and the ratio $R_{\rm max}/h$ decreases towards larger scalelenghths.



[4] M. Kregel, P.C. van der Kruit & R. de Grijs, MNRAS 334, 646 (2002); M. Kregel & P.C. van der Kruit, MNRAS 355, 143 (2004)

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[5].

- This model predicts substantial age changes across disks, which are not observed[6].
- 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.

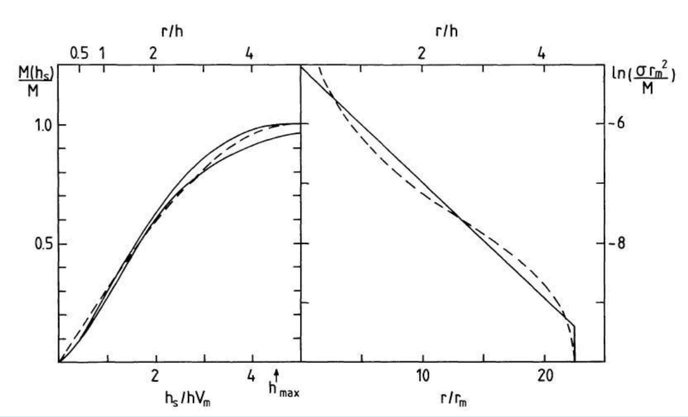
[5] Larson, MNRAS 176, 31 (1976)
[6] de Jong, A.&A. 313, 377 (1996)

II. Inhibition of star formation when the gas surface density falls below some threshold (surface) density for local instability[7].

- The Goldreich-Lynden-Bell criterion for stability of a gaseous layer gives a poor prediction for the truncation radii[8].
- Another problem is that observations of the rotation curves of a some galaxies (e.g. NGC 5907 and NGC 4013[9]) 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).

[7] Fall & Efstathiou, MNRAS 193, 189 (1980); Schaye, Ap.J. 609, 667 (2004)
[8] van der Kruit & Searle, A.&A. 110,61 (1982)
[9] 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[10].



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

- If the collapse occurs from a Mestel sphere[11] (that has uniform density and angular velocity) with detailed conservation of specific angular momentum[12] 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.

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

IV.

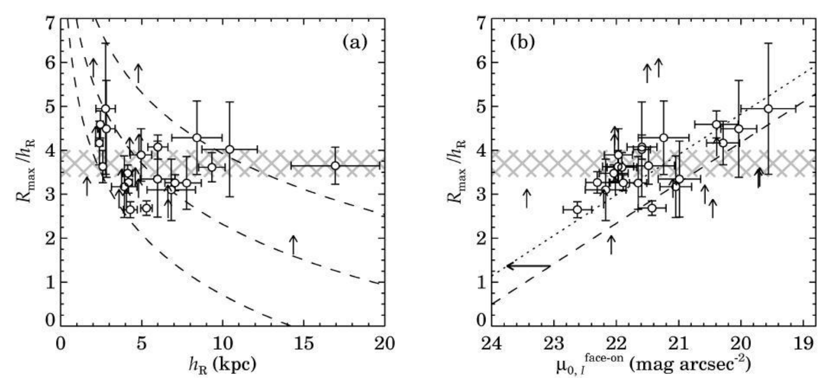
It is also possible that substantial redistribution of angular momentum takes place, such that it is unrelated to the initial distribution in the material that formed the disks.

- Bars may play an important role in this, as suggested by Erwin et al.[13].
- 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[14].

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

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

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 $\mu_{\circ,{\rm fo}}$.[15]



[15] 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

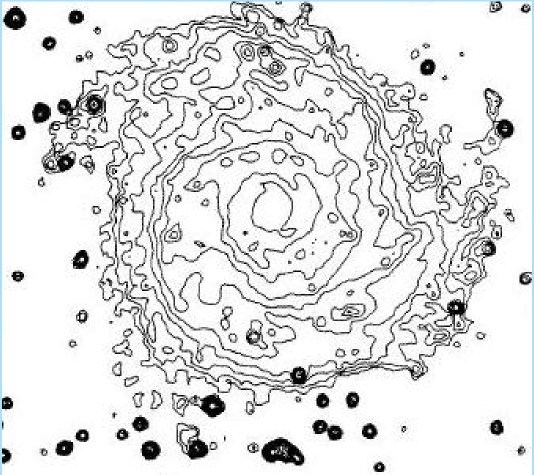
Due to line-of-sight integration truncations should more difficult to detect in face-on galaxies than in edge-on ones.

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.[16]

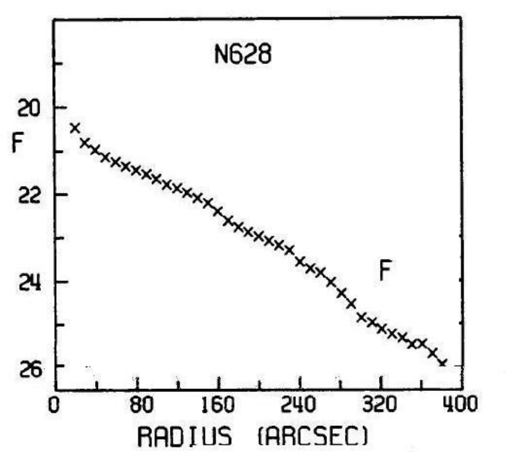
[16] Wevers, van der Kruit & Allen, A.&A.Suppl. 66, 505 (1986), van der Kruit, A.&A. 192,117 (1988)

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

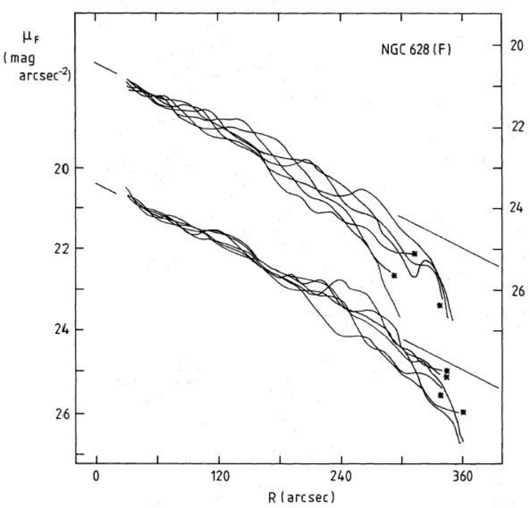


The usual procedure is to derive the inclination and major axis from kinematics and then proceed to make an azimuthally averaged radial surface brightness profile.

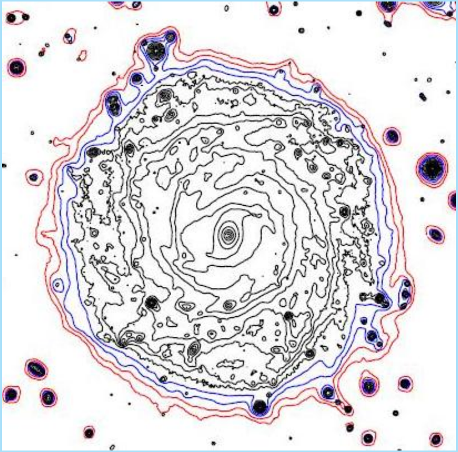
This smoothes out the sharp decline.



It can be recoverd by averaging in smaller sectors.



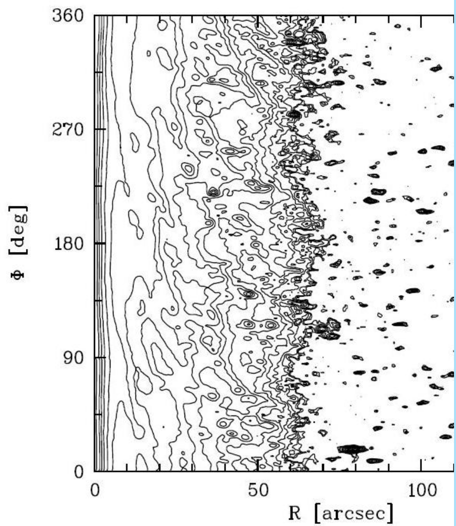
The effects is seen here as well in the red and blue contours of NGC 5923.[17]



[17] 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.



The work of Pohlen and collaborators

Extensive work has been performed by Michael Pohlen and collaborators.

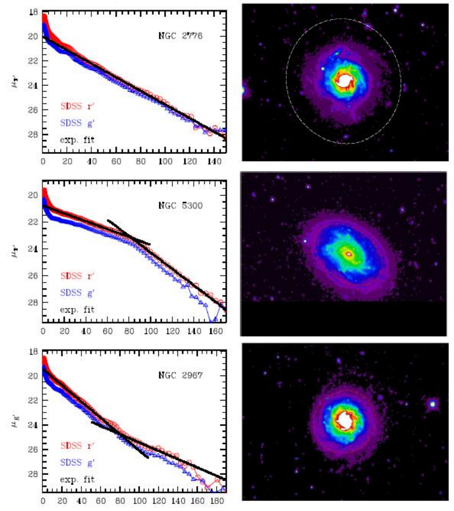
- A sample of moderately inclined systems[18] has been studied through ellipse-fitting of isophotes in SDSS data.
- A few edge-on systems[19] have been studied using a decomposition thecnique.

[18] Pohlen & Trujillo, A.&A. 454, 759 (2006)
[19] 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

The ones with an upbending break, however, almost all have indications for interactions or mergings in their outer parts.



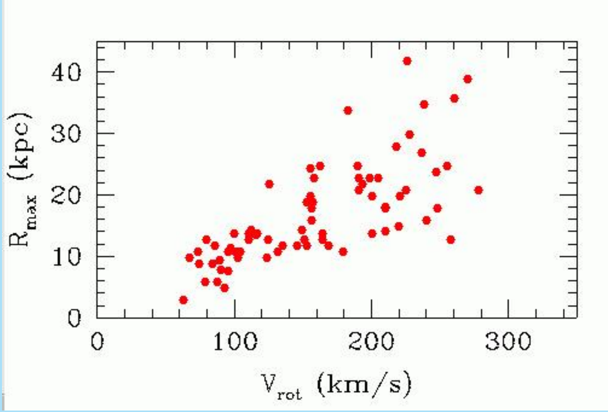
$R_{\rm max}$ versus $V_{\rm rot}$ and $R_{\rm max}/h$ versus h

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

We will do this only for edge-on galaxies.

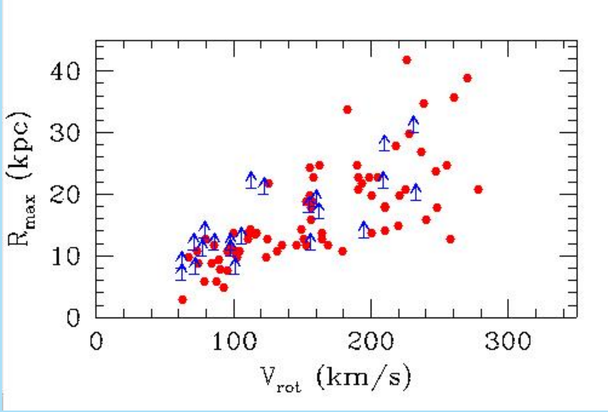
Here is the data from various edge-on samples.

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



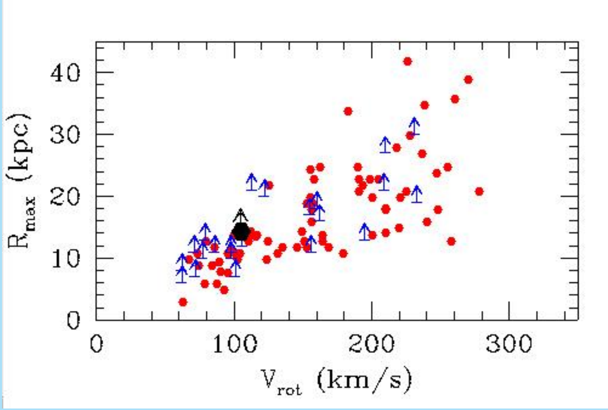
Now include the lower limits to the truncation radius from the same samples.

This does not change the picture much.



For the interest I add the point for NGC 300[20].

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

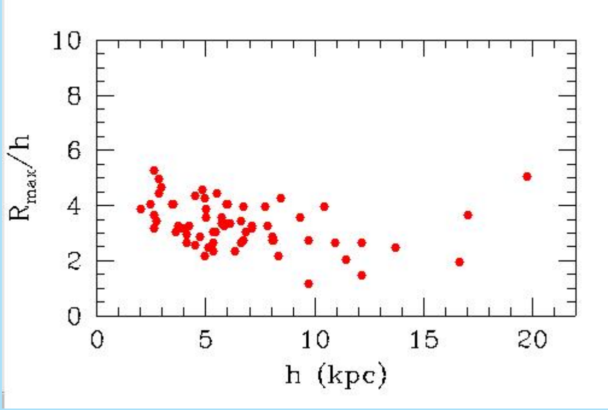


[20] Bland-Hawthorn et al., Ap.J. 629, 249 (2005)

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

Here is the data for all edge-on galaxies.

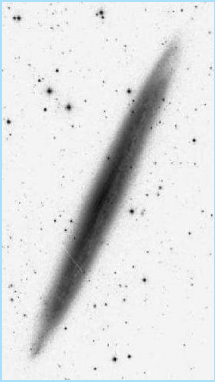
Note the absence of the anti-correlation predicted by Schaye.

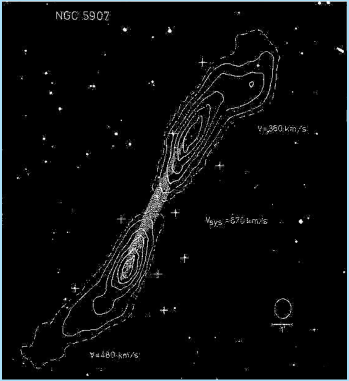


Warps in HI-disks

Observations of HI-warps

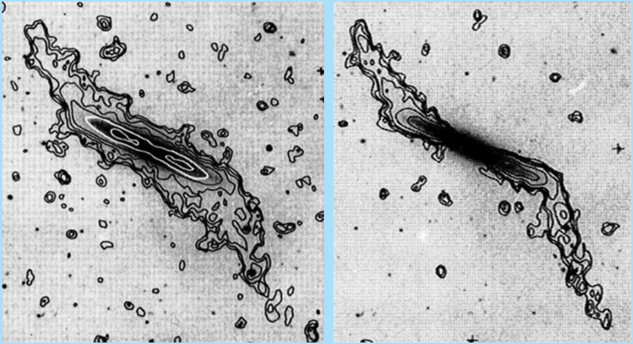
- Warps in the HI in external galaxies are most readily observed in edge-on systems as NGC 5907[21].





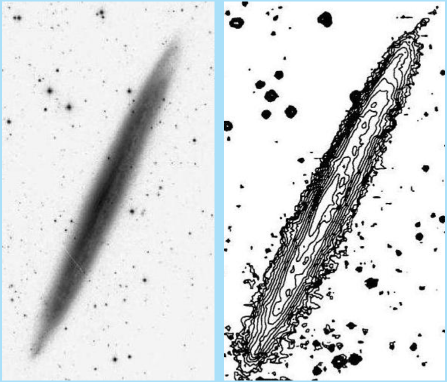
[21] R. Sancisi, A.&A. 74, 73 (1976)

- An extreme example is "prodigious warp" in NGC 4013[22].
- The warp is very symmetric and starts suddenly near the end of the optical disk (see the extreme channel maps on the left).



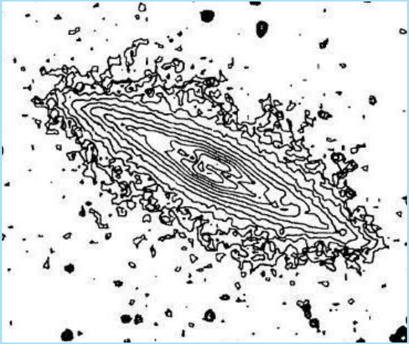
[22] R. Bottema, G.S.Shostak & P.C. van der Kruit, Nature 328, 401 (1987); R. Bottema, A.&A. 295, 605 (1995) and 306, 345 (1996)

- It is interesting to note that the NGC 5907 has a clear and sharp truncation[23] in its stellar disk, where also the warp starts.



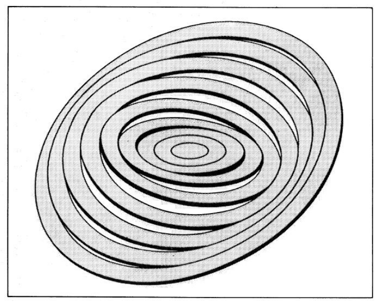
[23] P. C. van der Kruit & L. Searle, *op. cit.*

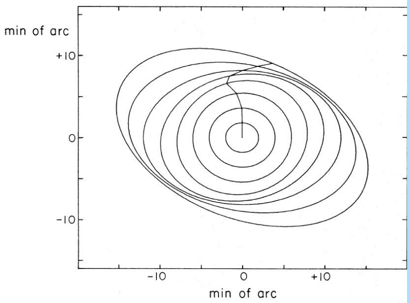
- NGC 4013 also has a clear truncation[24] in its stellar disk. The three-dimensional analysis[25] does confirm that in deprojection the warp strats very close to the truncation radius.



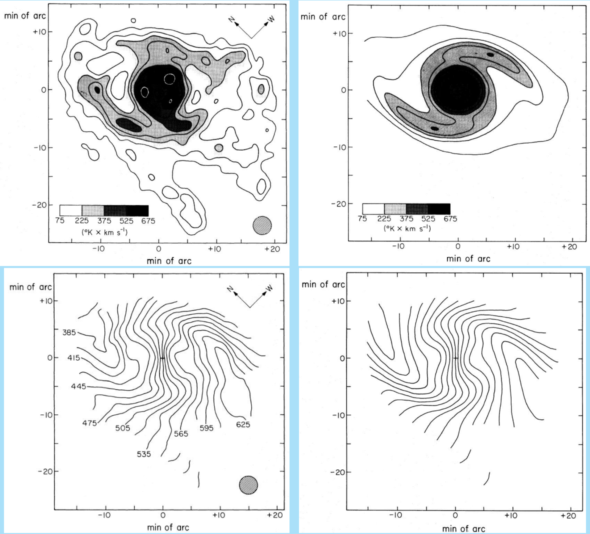
[24] P. C. van der Kruit & L. Searle, *op. cit.*
[25] R. Bottema, *op. cit.*

- Warps were already seen in less inclined systems, such as M83[26].
- These "kinematic warps" were fitted with so-called "tilted-ring models".

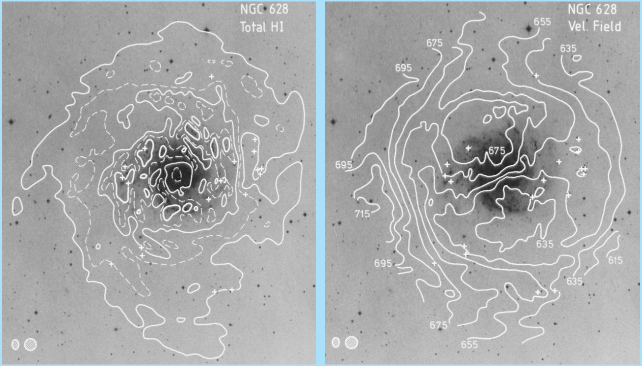




[26] D.H. Rogstad, I.A. Lockhart & M.C.H. Wright, Ap.J. 193, 309 (1974)

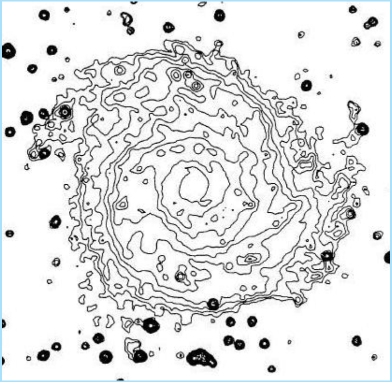

min of arc
+10
0
-10
-20
75 225 375 525 675
(°K × km s^{-1})
-10
0
+10
+20
min of arc
N
W
385
415
445
475
505
535
565
595
625

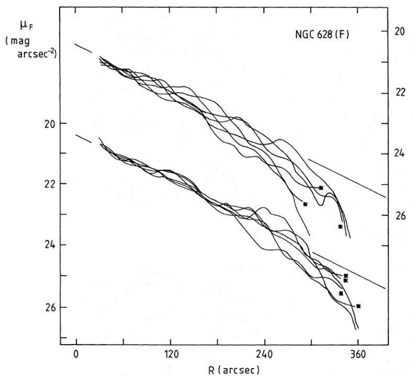
- NGC 628 is almost completely face-on.
- The HI-velocity field shows a complecated pattern, that shows that in the tilted-ring model the rings actually go through the plane of the sky[27].



[27] G.S. Shostak & P.C. van der Kruit, A.&A. 132, 20 (1984)

- The radial luminosity profiles[28] show evidence for a truncation.
- This truncation coincides with the onset of the warp.





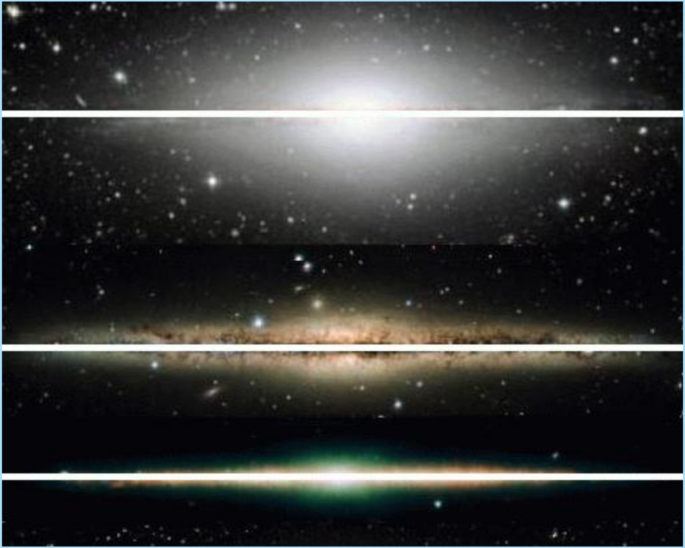
[28] G.S. Shostak & P.C. van der Kruit, *op. cit.*; P.C. van der Kruit, A.&A. 192, 117 (1988)

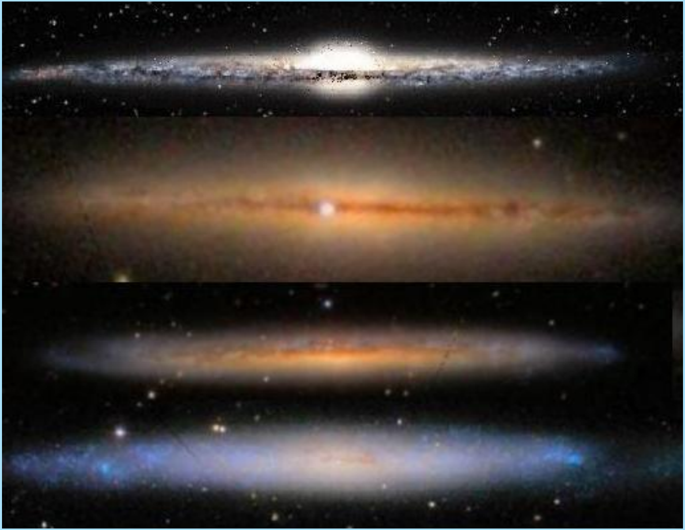
Disks are very flat.

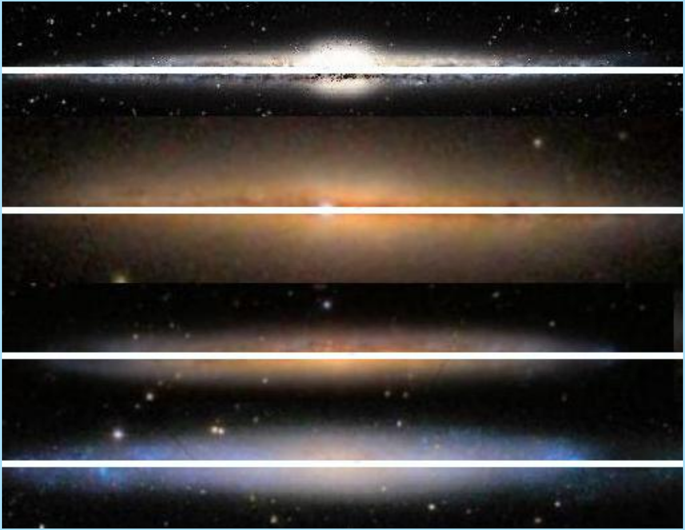
First we look at stellar disks.

Here are a few edge-on galaxies.

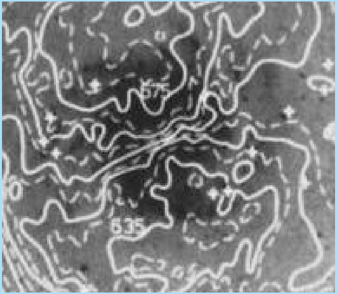
Note from the dustlanes that the disks are **very** flat.

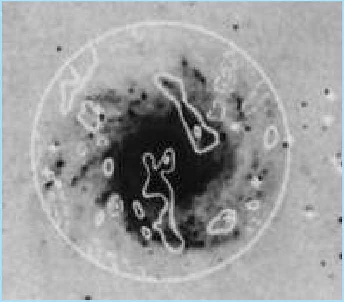






The residual velocity field in the inner parts of NGC628 after subtraction of the rotation field, has an r.m.s. velocity of only (3-4) km/s.





A vertical velocity of 4 km/s corresponds in the Solar Neighborhood to an amplitude of 45 pc, so this shows also that disks are very flat.

Systematics of HI-warps

- Briggs[29] formulated a set of rules of behaviour for HI- warps.

RULES OF BEHAVIOR FOR GALACTIC WARPS

F. H. Briggs
Kapetyn Astronomical Institute, University of Groningen, and Department of Physics and Astronomy, University of Pittsburgh
Received 1989 July 21; accepted 1989 September 19

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.

[29] F.H. Briggs, Ap.J. 352, 15 (1990)

- The most important aspects of Brigg's rules for the present discussion are:
  1. The HI layer typically is planar within R_{25}, but warping becomes detectable near $R_{Ho} = R_{26.5}$.
  2. Warps change character at a transition radius near R_{Ho}.
  3. ......
  4. The outer warp defines a reference frame.
- The onset of HI-warps seems to be at about the radius of the truncation in the stellar disk
- This might mean that the inner stellar disk formed first with a truncation and the HI in the warp fell in later with another orientation of the angular momentum.

The García-Ruiz et al. sample

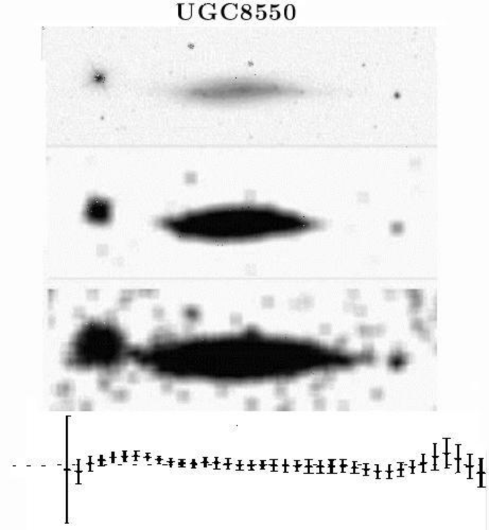
The García-Ruiz et al. sample

- Inigo García-Ruiz[30] presented HI observations of a sample of edge-on galaxies ("Hunting for warps").
- His sample consisted of 26 edge-on galaxies in WHISP[31].
- At least 20 show evidence for an HI warp.
- Unfortunately, the optical surface photometry could not be calibrated.
- So I used the Sloan Digital Sky Survey (SDSS) to see if there are truncations and if so, where are the warps start w.r.t. to these.

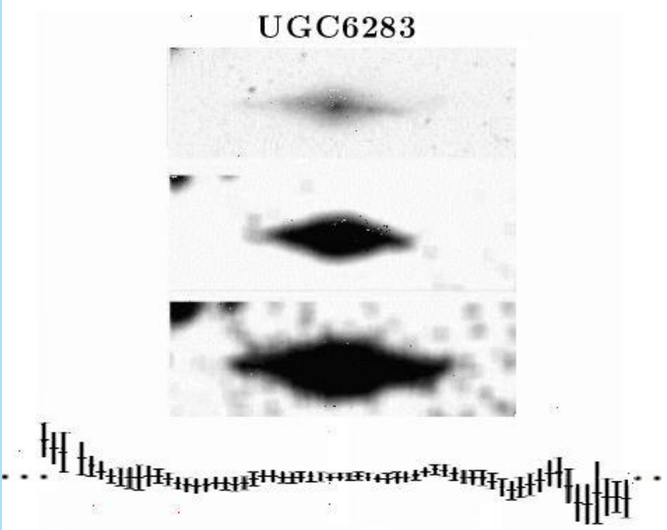
[30] Ph.D. Thesis, University of Groniongen (2001); see also I. García-Ruiz, R. Sancisi & K.H. Kuijken, A.&A. 394, 796 (2002)

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

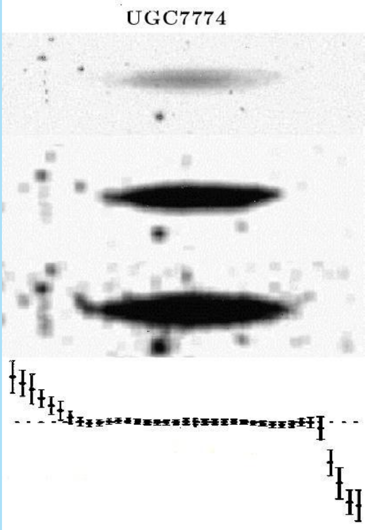
UGC 8550: No truncation and no warp



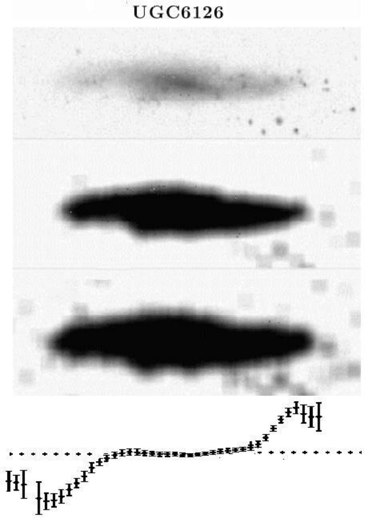
UGC 6283: No truncation, warp at larger radius.



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



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



- Summarizing we have:[32]
  - For 4 galaxies the HI does not extend beyond the optical radius; of these 2 have a truncation.
  - There is 1 galaxy with no truncation and no warp.
  - There are 3 galaxies with a warp, but no truncation; for one of these the warp starts beyond the optical radius.
  - There is 3 galaxies with a truncation, but no warp.
  - There are 12 galaxies with both a warp and a truncation.
- The galaxies in the second, third (except the one with a warp at large distance) and fourth item could be examples where the warp is too close to the line of sight.

[32] P.C. van der Kruit, A.&A. 466, 883, 2007.

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

Discussion

I. Properties of warps

- Properties of warps can be summarized as follows:
  - All galaxies with extended HI disks have warps (García-Ruiz et al.).
  - Many galaxies have relatively sharp truncations (van der Kruit & Searle; Kregel & van der Kruit; this study).
  - In edge-on galaxies the HI warps sets in just beyond the truncation radius (this study), for less inclined systems it sets in near the Holmberg radius (Briggs).
  - 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 (Casertano, Bottema, this study).
  - The onset of the warp is abrupt and discontinuous (this discussion) and there is a steep slope in HI-surface density at this point (García-Ruiz et al.).
  - Inner disks are extremely flat (this discussion) and the warps define a single "new reference frame" (Briggs).

Discussion

II. Origin of warps

- The inner disk (mostly stars) and the warped outer disk (mostly HI) are distinct components.
- They probably have distinct formation histories, during different epochs.
- Inner disks form initially and settle as massive, rigid, flat structures.
- Warps result form 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.
- This is consistent with the model where truncations result from a maximum specific angular momentum in the material that formed the disk.

Discussion

Summary

- *Truncations are a common feature in edge-on stellar disks.*
- *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.*