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

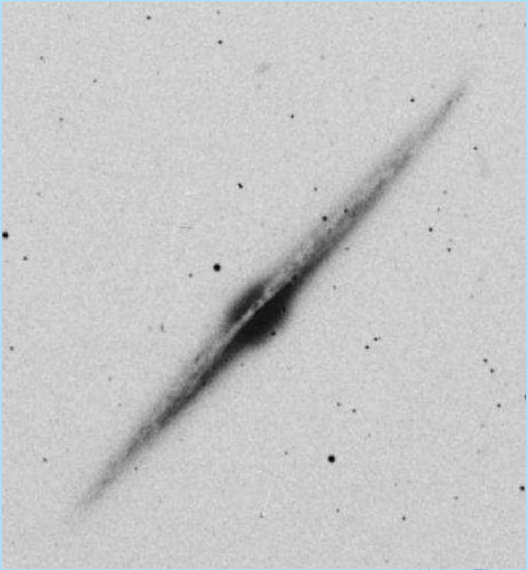
Piet van der Kruit
Kapteyn Astronomical Institute
University of Groningen
the Netherlands

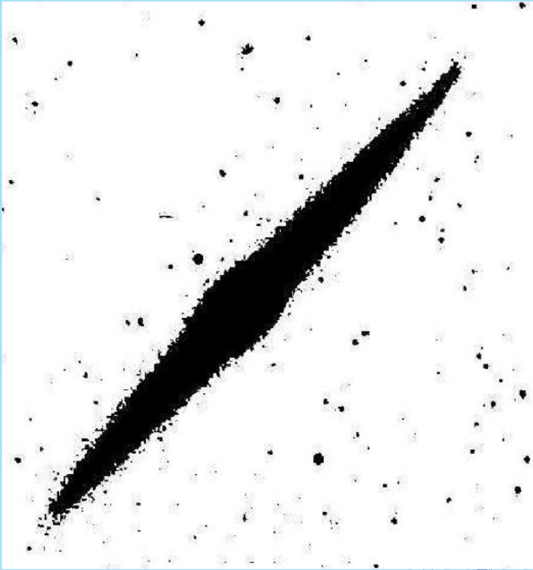
February 2007

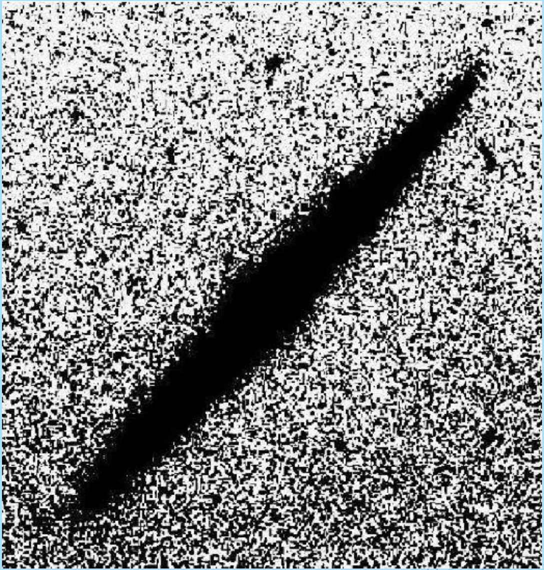
Observations of truncations

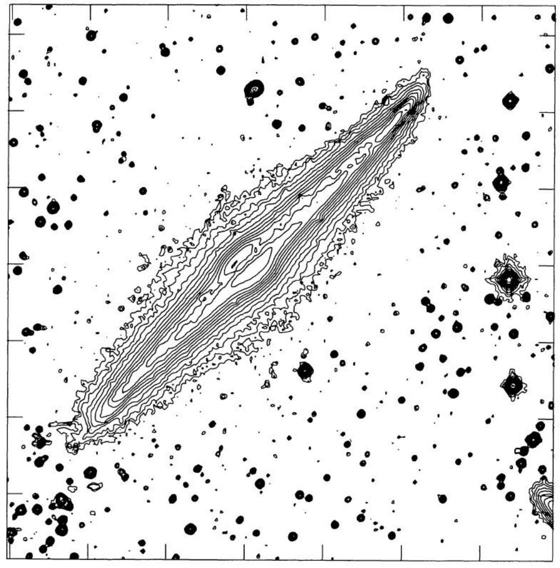
- In edge-on spiral galaxies it was noted[1] that the radial extent did not grow with deeper and deeper photographic exposures.
- Especially when a bulge was present the minor axis did grow with deeper images.
- A prime example of this phenomenon of so-called disk truncations is the galaxy NGC 4565.

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

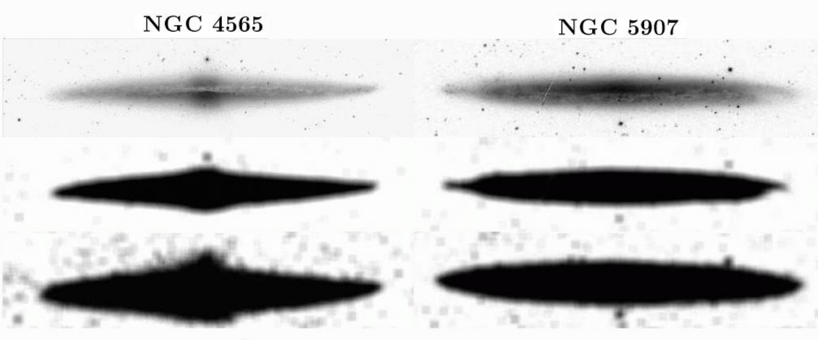








Summarizing:



- 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.

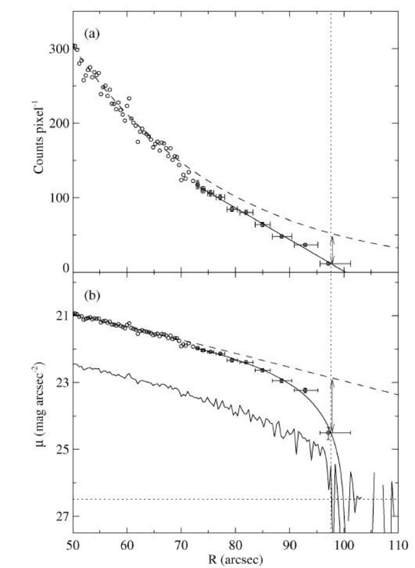
- Then the projected surface distribution will be

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

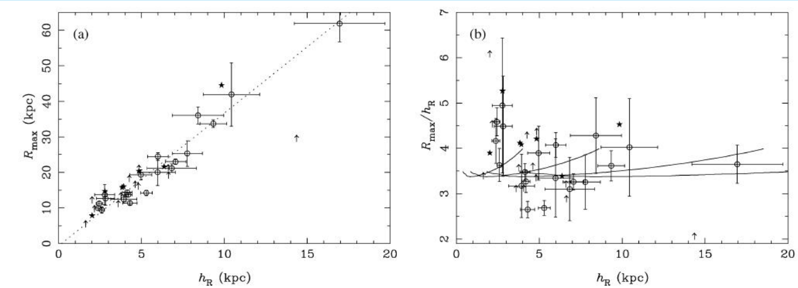
where $K_1(R/h)$ is a Bessel function of the first kind, that approaches exp (R/h) at large R.

- For $R > R_{max}$ the distribution $\mu(R,z$ drops quickly before R_{max}.

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


(a)
Counts pixel^{-1}
300
200
100
0
(b)
μ (mag arcsec^{-2})
21
23
25
27
50
60
70
80
90
100
110
R (arcsec)

- More recent analyses[3] 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.



[3]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)

Origin of truncations

There are a number of suggestions that have been proposed.

- The truncations are the current extent of slowly growing disks (from the inside to the outside) from accretion of external material[4].
- This model predicts substantial age changes across disks, which are not observed[5].
- 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.

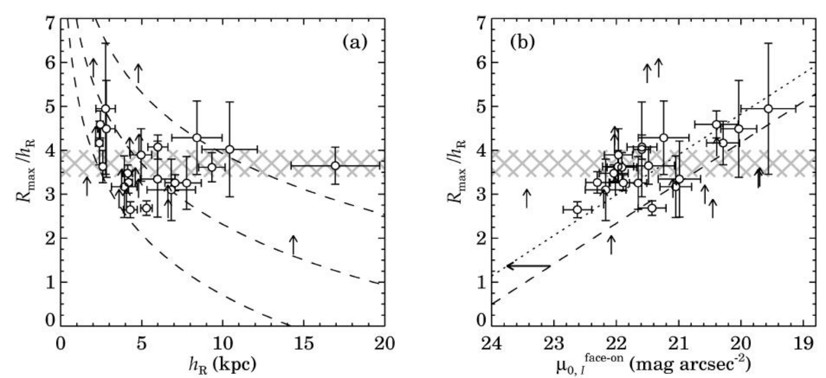
[4] R.B. Larson, MNRAS 176, 31 (1976)
[5] R.S. de Jong, A.&A. 313, 377 (1996)

- Inhibition of star formation when the gas surface density falls below some threshold (surface) density[6].
- The Goldreich-Lynden-Bell criterion for stability of a gaseous layer gives a poor prediction for the truncation radii[7].
- Another problem is that observations of the rotation curves of a some galaxies as NGC 5907[8] and NGC 4102[9] show features near the truncations that indicate that the **mass** distributions are also truncated.

---

[6] M. Fall & G. Efstathiou, MNRAS 193, 189 (1980); J. Schaye, Ap.J. 609, 667 (2004)
[7] P.C. van der Kruit & L. Searle, A.&A. 110,61 (1982)
[8] S. Casertano, MNRAS 203, 735 (1983)
[9] R. Bottema, A.&A. 306, 345 (1996)

- On the other hand, the rough constancy of surface density at the truncations[10] would fit this model.

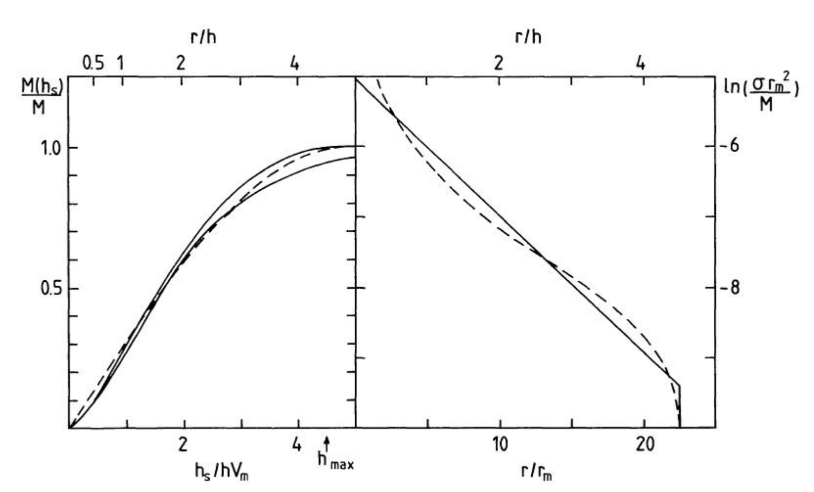


[10] Kregel & van der Kruit, *op. cit.*

- The truncation corresponds to a maximum in the specific angular momentum in the protogalaxy[11].
- 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.
- The constancy of surface density at the truncation does require, however, some redistribution of angular momentum in the disk.

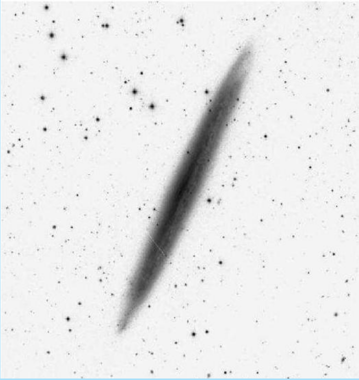
---

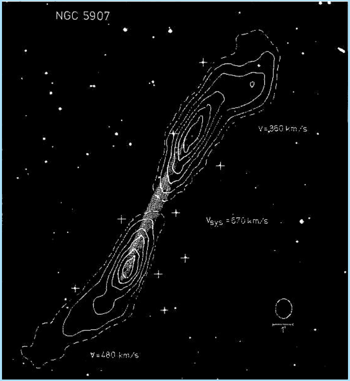
[11] P.C. van der Kruit, A.&A. 173, 59 (1987)
[12] L. Mestel, MNRAS 126, 553 (1963)
[13] Fall & Efstathiou, *op. cit.*


r/h
0.5
1
2
4
$\frac{M(h_s)}{M}$
1.0
0.5
2
4
h_{max}
h_s/hV_m
r/h
2
4
$\ln(\frac{\sigma r_m^2}{M})$
-6
-8
10
20
r/r_m

Observations of HI-warps

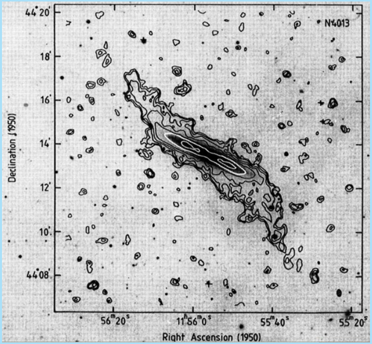
- Warps in the HI in external galaxies are most readily observed in edge-on systems as NGC 5907[14].

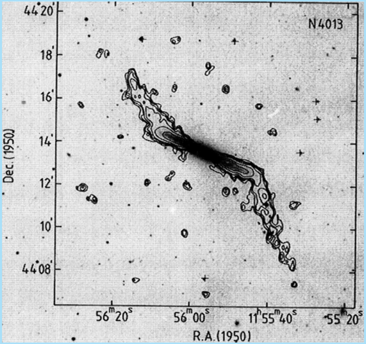




[14] R. Sancisi, A.&A. 74, 73 (1976)

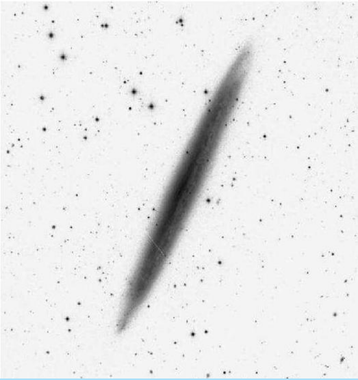
- An extreme example is "prodigious warp" in NGC 4013[15].
- The warp is very symmetric and starts suddenly near the end of the optical disk (see the extreme channel maps on the left).

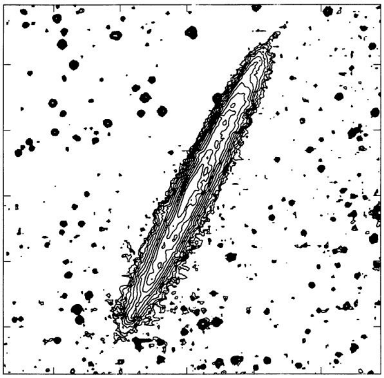




[15] R. Bottema, G.S.Shostak & P.C. van der Kruit, Nature 328, 401 (1987); R. Bottema, A.&A. 295, 605 (1995) and 306, 345 (1996)

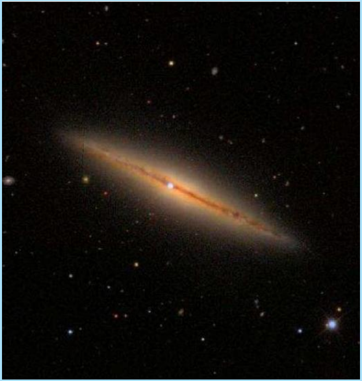
- It is interesting to note that the NGC 5907 has a clear and sharp truncation[16] in its stellar disk, where also the warp starts.

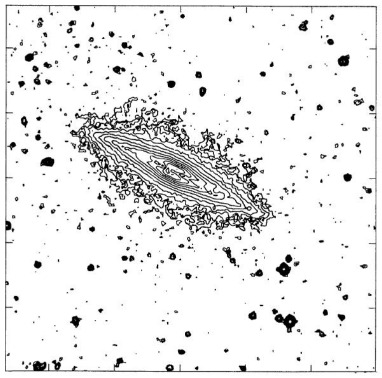




[16] P. C. van der Kruit & L. Searle, *op. cit.*

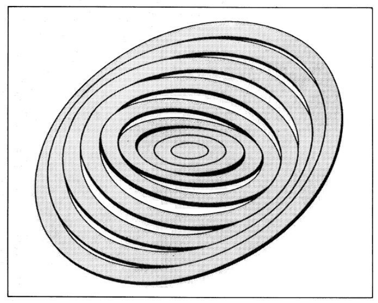
- NGC 4013 also has a clear truncation[17] in its stellar disk. The three-dimensional analysis[18] does confirm that in deprojection the warp strats very close to the truncation radius.

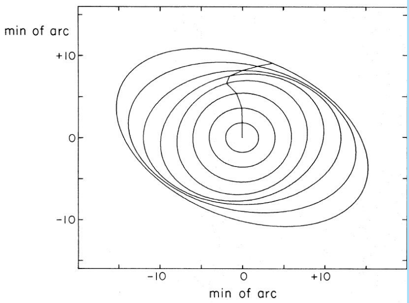




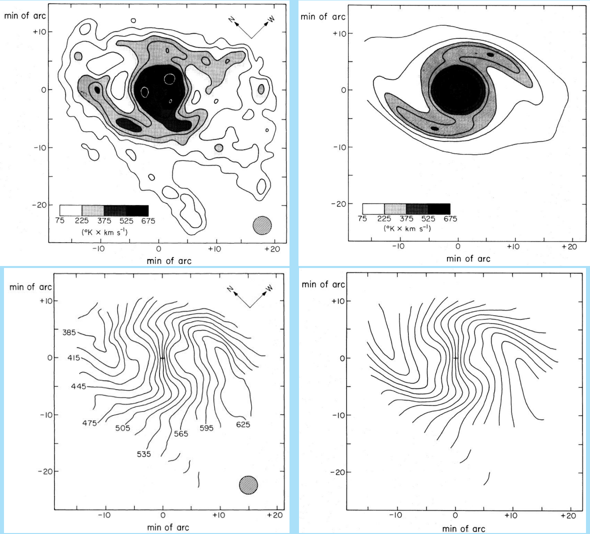
[17] P. C. van der Kruit & L. Searle, *op. cit.*
[18] R. Bottema, *op. cit.*

- Warps were already seen in less inclined systems, such as M83[19].
- These "kinematic warps" were fitted with so-called "tilted-ring models".

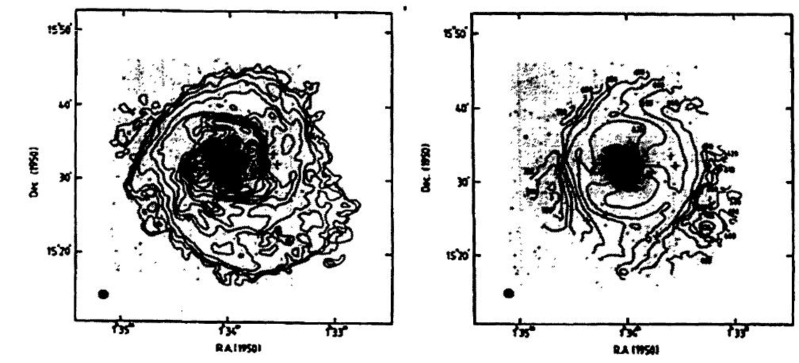




[19] D.H. Rogstad, I.A. Lockhart & M.C.H. Wright, Ap.J. 193, 309 (1974)

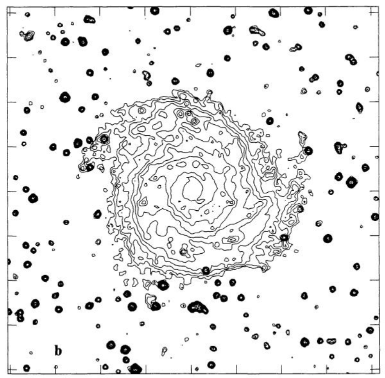

min of arc
+10
0
-10
-20
75 225 375 525 675
(°K × km s^{-1})
-10
+20
N
W
385
415
445
475
505
535
565
595
625

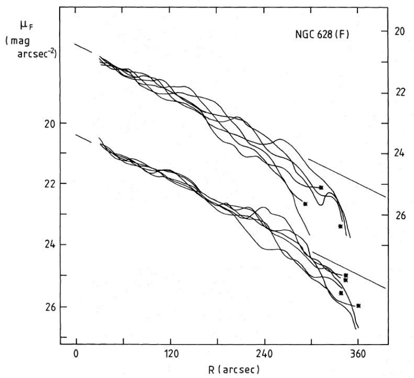
- NGC 628 is almost completely face-on.
- The HI-velocity field shows a complecated pattern, that shows that in the tilted-ring model the rings actually go through the plane of the sky[20].



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

- The radial luminosity profiles[21] show evidence for a truncation.
- This truncation coincides with the onset of the warp.





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

Systematics of HI-warps

- Briggs[22] 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 $R_{\rm Ho} = R_{26.5}$. Warping within $R_{\rm Ho}$ 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 $R_{\rm Ho}$.
3. For radii larger than $R_{\rm Ho}$, 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.

[22] 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

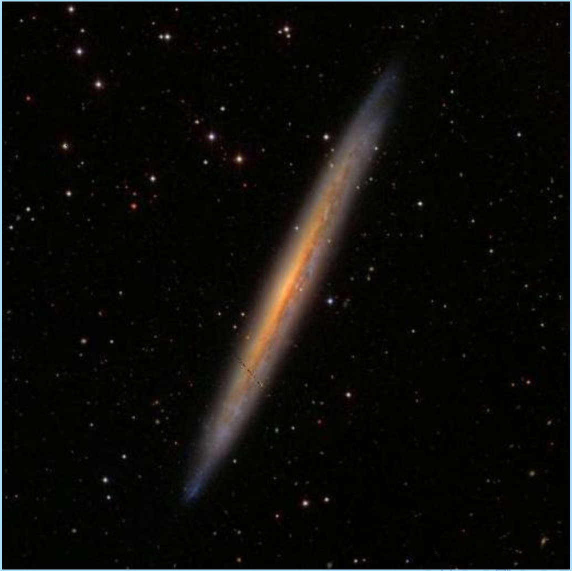
- Inigo García-Ruiz[23] presented HI observations of a sample of edge-on galaxies ("Hunting for warps").
- His sample consisted of 26 edge-on galaxies in WHISP[24].
- At least 20 show evidence for an HI warp.
- Unfortunately, the optical surface photometry could not be calibrated.
- So my aim is th investigate 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 are the warps start w.r.t. to these.

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

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

The use of the SDSS

- I will show the method for NGC 5907 using the Sloan Digital Sky Survey.
- I turn the data into 8-bit mode, then into grey-scale and subsequently into inverse video.
- Then I produce two clipped images, one called the "Shallow stretch", clipped at a level of 215 and a "Deep stretch" at 245. Experimenting shows that the choice of these twop values is optimal for my purpose.
- Finally, I heavely smooth the resulting images.
- The I print the results and simply measure the extents along the major and the minor axes.



- There is a difference in extent of the major axis and of the flattening ratio (major over minor axis) between shallow and deep clip.
- I repeat this for the edge-on galaxies in the van der Kruit & Searle sample[25] (NGC 891 not available in SDSS).
- Since in the García-Ruiz et al. sample a few are not avaialble with the SDSS I also tried the Digital Sky Survey 2 (red).

[25] P.C. van der Kruit & L. Searle, A.&A. 95, 105 and 116 (1981); 110, 61 and 79 (1982)

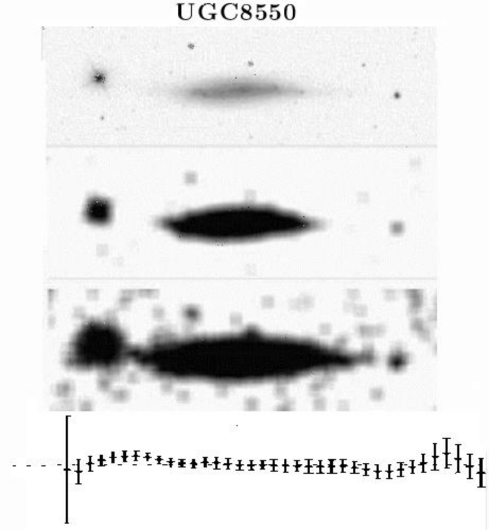
	major axis ratio	flattening ratio
	SDSS	
NGC 4013	1.10	1.41
NGC 4217	1.08	1.22
NGC 4244	1.09	1.15
NGC 5465	1.02	1.20
NGC 5023	1.19	1.07
NGC 5907	1.06	1.16
NGC 7814	1.18	1.03
	DSS	
NGC 891	1.07	1.49
NGC 4013	1.10	1.23
NGC 4217	1.04	1.15
NGC 4244	1.03	1.06
NGC 4565	1.04	1.21
NGC 5023	1.30	0.95
NGC 5907	1.07	1.10
NGC 7814	1.44	1.05

- Comparison with the actual surface photometry shows that in the SDSS the clips correspond to about 26.5 and 27.5 B-mag arcsec^{-2}; in the DSS2 it is about 25.5 and 26.5.
- Truncations have the signature of a small increase in the major axis and a larger one in the flattening.
- NGC 5023 is a pure-disk system that has a truncation at faint levels that was very difficult to see in the surface photometry.
- All other truncations are found back in the SDSS data.
- NGC 4244 is a pure-disk system with a truncation visible at about the surface brightness where the DSS can go. This one is not found back in the DSS data.
- NGC 7814 is bulge-dominated.
- The criteria for the presence of a truncation then is that the major axis ratio less than 1.1 and the flattening ratio larger then 1.1.

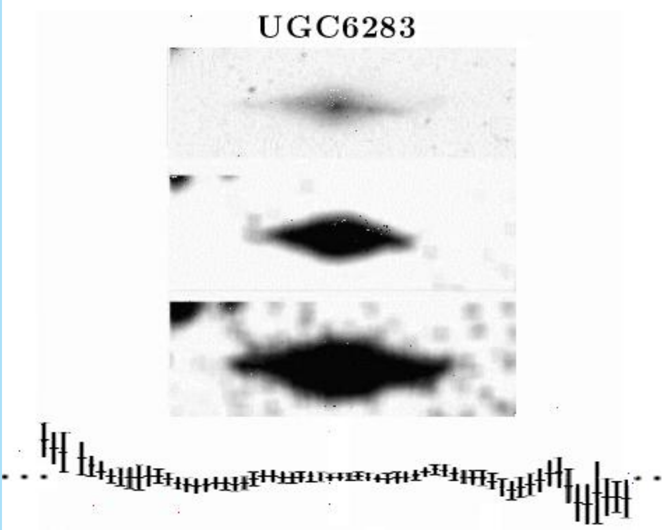
Results

- The application to the the García-Ruiz et a. sample gives:
  - Two galaxies have very different sides and will not be considered.
  - Galaxies with a clear truncation: **17**
  - Galaxies with no clear evidence for a truncation: **6**
  - In 4 cases the HI does not extend significantly beyond the optical image.
- I will now show a few examples.

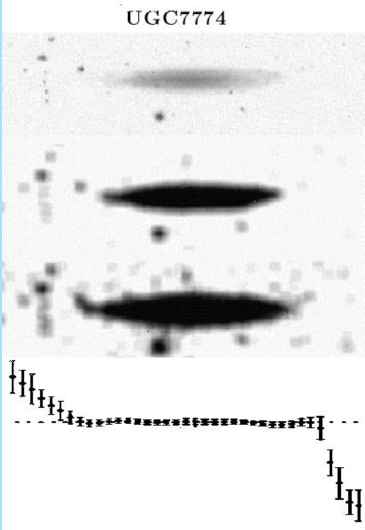
UGC 8550: No truncation and no warp



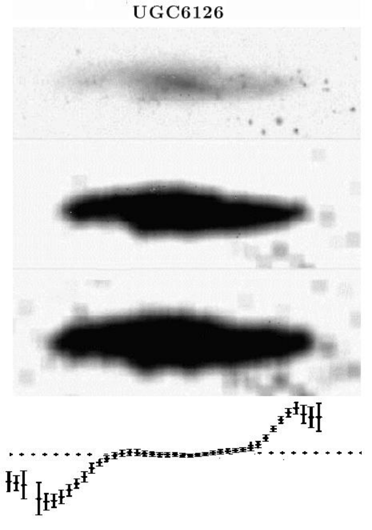
UGC 6283: No truncation, warp at larger radius.



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:
  - 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.

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}.

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 (Garcí-Ruiz et al.).
  - Inner disks are extremely flat (this discussion) and the warps define a single “new reference frame” (Briggs).

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.

1. The SDSS can be used to investigate the presence of truncations in the disk light distributions.
2. The edge-on galaxiess in the sample of García-Ruiz et al. show in 17 out of 23 cases truncations in their stellar disks.
3. When an HI-warp is present it starts at about 1.1 R_{max}.
4. There is a discontinuous and abrupt transition to the warped disk, occuring at the truncation of the stellar disk, where also the HI surface density drops steeply.
5. These findings suggest that the inner flat disk and the outer warped disk are distinct components with a quite separate formation history, probably during quite different epochs.
6. This picture is consistent with the view that truncations result from the maximum specific angular momentum in the material that formed the inner disk.