

The stars and gas in outer parts of galaxy disks: Extended or truncated – flat or warped?

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Abstract. I review observations of truncations of stellar disks and models for their origin, compare observations of truncations in moderately inclined galaxies to those in edge-on systems and discuss the relation between truncations and HI-warps and their systematics and origin. Truncations are a common feature in edge-on stellar disks, but the relation of truncations in face-on to those in edge-on galaxies needs further clarification. 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 this model does probably require some re-distribution of angular momentum. HI-warps start just beyond the truncation radius and disks and warps appear 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 the angular momentum. The L^AT_EX-Beamer presentation of this review is available in pdf-format at www.astro.rug.nl/~vdkruit/jea3/homepage/vaticanpres.pdf.

1. Truncations in edge-on galaxies

Truncations were first found in edge-on spiral galaxies, where the remarkable feature was noted that the radial extent did not grow with deeper photographic exposures (van der Kruit 1979). Especially, when a bulge was present the minor axis did grow considerably on IIIA-J images compared to the Palomar Sky Survey IIa-D exposures in contrast with the major axes. Prime examples of this phenomenon of “truncations” (originally also called “cut-offs”) are the edge-on galaxies NGC 4565 and NGC 5907 (Fig. 1). The truncations appear very sharp, although of course not infinitely. Van der Kruit & Searle (1981) state: “*This cut-off is very sharp with an e-folding of less than about 1 kpc, based on the spacing of the outer isophotes.*” Sharp outer profiles are actually obtained after deprojecting near-IR observations of edge-on galaxies (e.g. Florido et al. 2006).

Various models have been proposed for the origin of truncations:

I. The truncations are the current extent of disks that are growing from the inside out from accretion of external material (Larson 1976). This predicts substantial age gradients across disks, which are not observed (de Jong 1996b). Current thinking is that disks formed in an initial monolythic collapse followed by a protracted period of infall of gas and capture of dwarfs companions or by a slow continuing process of merging of existing systems in a hierarchical picture.

II. Inhibition of star formation when the gas surface (or space?) density falls below a threshold for local stability (Fall & Efstathiou 1980; Kennicutt 1989; Schaye 2004). The Goldreich-Lynden-Bell criterion for stability of gas layers

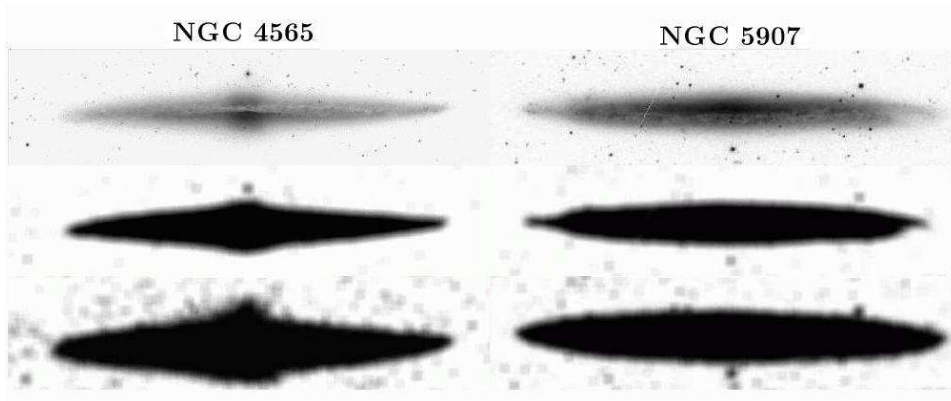


Figure 1. NGC4565 and NGC 5907 at various light levels (from van der Kruit (2007)).

gives a poor prediction for the truncation radii (van der Kruit & Searle 1982). Another problem is that the rotation curves of some galaxies –e.g. NGC 5907 and NGC 4013 (Casertano 1983; Bottema 1996)– show features near the truncations that indicate that the **mass** distributions are also truncated. Schaye predicts an anti-correlation between R_{\max}/h and h , which is not observed.

III. The truncation corresponds to a maximum in the specific angular momentum distribution in the protogalaxy (van der Kruit 1987). If the collapse occurs from a Mestel (1963) sphere (i.e. uniform density and angular rotation) with detailed conservation of specific angular momentum in the force field of a dark halo with a flat rotation curve, a roughly exponential disk results with a truncation at about 4.5 scalelengths. This provides at the same time an explanation for the exponential nature of disk as well as for the occurrence of the truncations.

IV. It is also possible that substantial redistribution of angular momentum, takes place, such that its distribution now 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. (2007). 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 (de Jong et al. 2007).

V. The magnetic model (Battener et al. 2002; Florido et al. 2006), in which a magnetic force breaks down as a result of star formation so that stars escape. The evidence for sufficiently strong magnetic fields needs strengthening.

Kregel & van der Kruit (2004) derive correlations of the ratio of the cut-off radius in terms of disk scalelengths with h itself and with the face-on central surface brightness $\mu_{o,fo}$ (Fig. 2). 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 $\mu_{o,fo}$, indicating approximate constant disk surface density at the truncations, as possibly expected by the star-formation threshold model. But this model predicts an anti-correlation between R_{\max}/h and h (Schaye 2004), which is not observed (see Fig. 2a). The maximum angular momentum hypothesis predicts that R_{\max}/h should not depend on h or $\mu_{o,fo}$ and such a model therefore requires some redistribution of angular momentum in the collapse or somewhat different initial conditions.

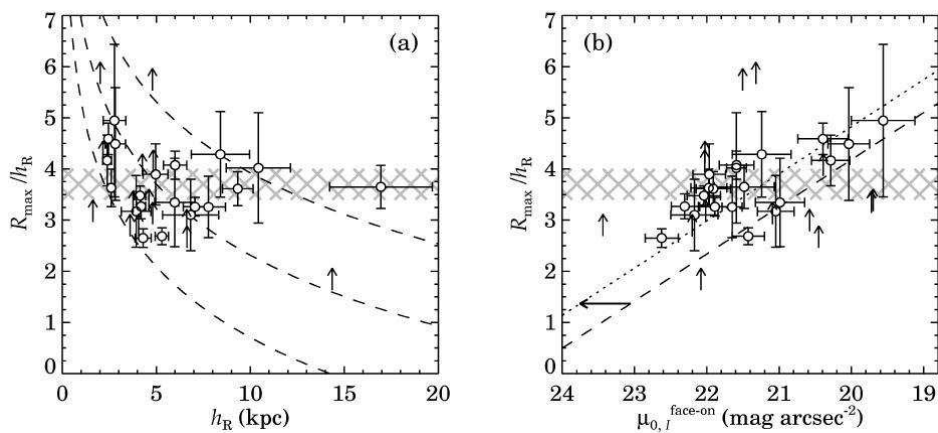


Figure 2. Correlations of R_{\max}/h with scalelength h and face-on central surface brightness $\mu_{\circ,fo}$ (from Kregel & van der Kruit 2006). The dotted lines show predictions from the star formation threshold model of Schaye (2004).

From these results concerning edge-on galaxies I conclude: **(1)** Many, but not all, stellar disks in edge-on galaxies show evidence for relatively sharp truncations in their radial distributions. **(2)** The model with a threshold in star formation as the origin of the truncations (Schaye 2004) is not in agreement with the observed distribution of R_{\max}/h with h . **(3)** If the truncation radius corresponds to a maximum in the specific angular momentum that existed already before the collapse and is conserved through the collapse, the initial configuration is either not identical to that of a uniform density, uniform angular momentum Mestel sphere and/or the conservation of specific angular momentum is not perfect.

2. 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. In face-on galaxies like NGC 628 (Shostak & van der Kruit 1984; van der Kruit 1988) an isophote map shows that the outer contours have a much smaller spacing than the inner ones. The usual analysis uses an inclination and major axis determined from kinematics (if available, otherwise this is estimated from the average shape of isophotes) and then determines an azimuthally averaged radial surface brightness profile. But this will smooth out any truncation if its radius is not exactly constant with azimuthal angle. The effects are nicely illustrated in the study of NGC 5923 by Pohlen et al. (2002) (their Fig. 9), which has isophotes in polar coordinates. The irregular outline shows that some smoothing out will occur contrary to observations in edge-on systems. Unless special care is taken we will always find a (much) less sharp truncation in face-on than in edge-on systems.

Table 1 summarizes the samples in the optical, which have been studied for the presence of truncations. For almost all of these galaxies the rotation velocity can be found using HYPERLEDA. Pohlen & Trujullo (2006) studied a sample

Table 1. Studies of truncations in galaxy disks

authors	orient.	trunc.	no trunc.	up-bend.
van der Kruit & Searle (1982)	edge-on	8	–	–
Pohlen et al. (2000)	edge-on	30	–	–
Pohlen et al. (2002)	face-on	3	–	–
Kregel & van der Kruit (2004)	edge-on	20	11	–
Pohlen & Trujillo (2006)	face-on	54	9	21
van der Kruit (2007)	edge-on	19	7	–
Pohlen et al. (2007)	edge-on	9	1	1

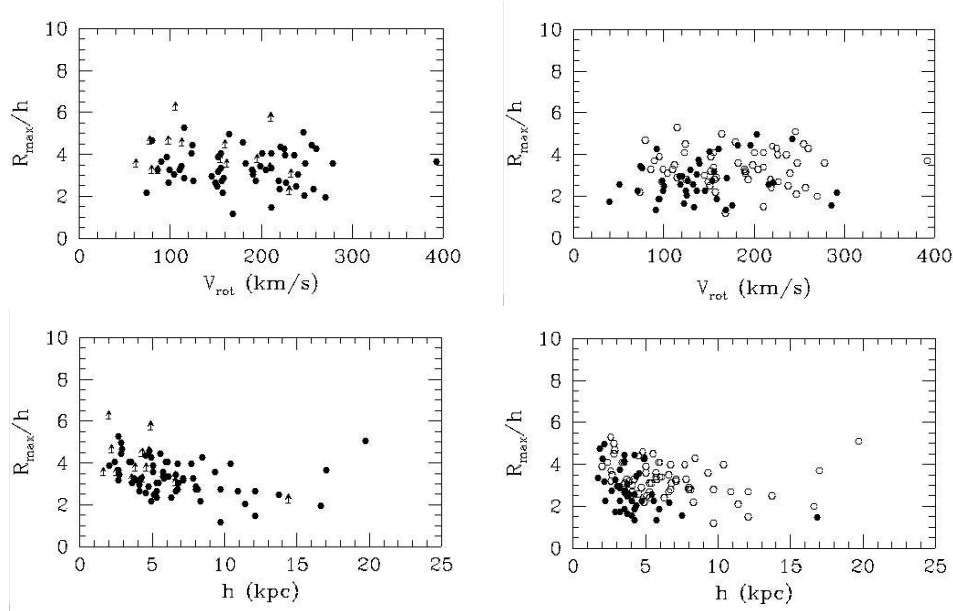


Figure 3. Plots of R_{\max}/h versus V_{rot} . The panel top-left has only edge-on systems; in the panel top-right these are open circles and filled dots show the moderately inclined systems of Type II (“down-bending break”). The lower panels show the same for R_{\max}/h versus h .

of moderately inclined systems through ellipse-fitting of isophotes in SDSS data. They distinguish three types of profiles: *Type I*: no break; *Type II*: downbending break; *Type III*: upbending break. First we will look at the ratio R_{\max}/h as a function of V_{rot} , both of which are distance independent. In Fig. 3 (top-left) I plot the data from the edge-on samples in Table 1. We see that these samples agree reasonably well among each other with R_{\max}/h ranging between about 2 and 5 and that there is no strong dependence on V_{rot} . In Fig. 3 (top-right) I compare this distribution to that for moderately inclined systems of Type II (“downbending break”). For these galaxies the distribution is similar to that for edge-on galaxies. The lower part of the figure has R_{\max}/h versus h ; this shows that the face-on samples lack galaxies of large scalelength.

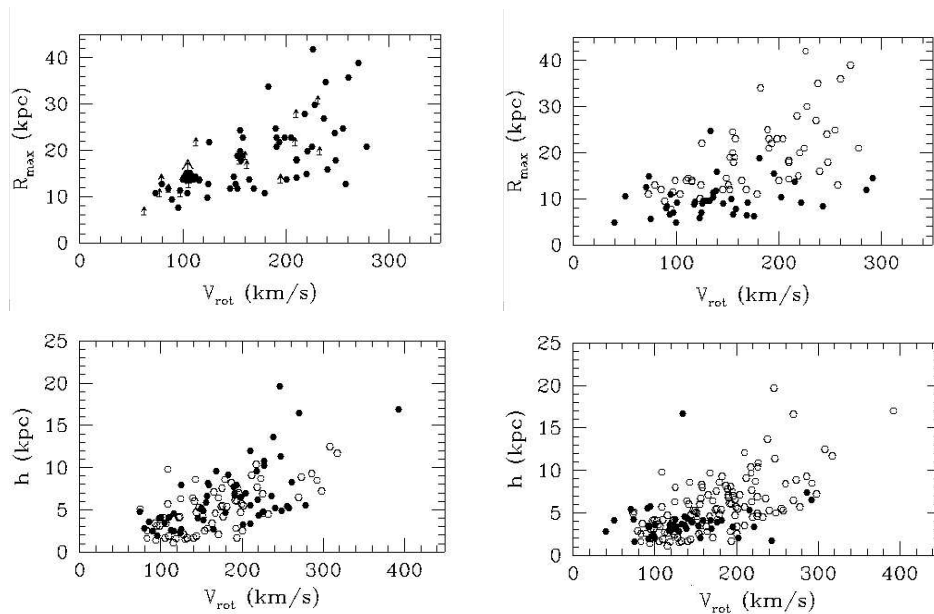


Figure 4. Plots of R_{\max} (top) and h (bottom) versus V_{rot} . The top-left panel has all edge-on galaxies, including lower limits. The large dot plus lower limit is NGC 300. In the top-right panel the edge-on systems are open circles; the filled dots are moderately inclined galaxies of truncation Type II. The lower-left panel has all edge-on systems (dots) and moderately inclined systems from de Jong (1996a) (circles). The panel lower-right has all points from panel lower-left as open circles and those from moderately inclined systems op Type II as filled dots.

Next I look at the correlation between R_{\max} and V_{rot} . Fig. 4 (top-left) shows the data from the edge-on samples. I also include the lower limits from these samples. Out of curiosity I add the point for NGC 300 (Bland-Hawthorn et al. 2005) at $V_{\text{rot}} \sim 105$ km/s, which has no truncation even at 10 scalelengths from the center. In spite of that it is not outside the distribution observed in edge-on systems. The reason is that it has a unusually small h for its V_{rot} ; *not an unusual extent* (in kpc) compared to its rotation.

In Fig. 4 (top-right) I have added the data for the moderately inclined galaxies. We see that the two samples have different distributions, the sample of Pohlen & Trujillo showing smaller R_{\max} , which may actually be expected from their method. But it also shows an absence of correlation of R_{\max} with V_{rot} , while these are clearly correlated in edge-on systems. Further study is required to establish whether or not truncations found in edge-on galaxies and in moderately inclined ones are indeed at the same thing.

Look now at h versus V_{rot} , which is a well-known scaling relation for spirals. In Fig. 4 (lower-left) the filled dots are the complete edge-on sample and the open circles are the sample of moderately inclined galaxies from de Jong (1996a). Note that the distributions are very similar, suggesting that there is no systematic difference in scalelengths measured in edge-on and face-on samples. Next I present the de Jong points also as open circles (Fig. 4 - lower-right) and compare

with the Pohlen & Trujillo sample of Type II (filled dots). These points again do not show the expected correlation.

I conclude from this section as follows: **(1)** Measurements of truncations in edge-on and face-on systems have fundamental differences. **(2)** There are no systematic differences in measurements of the scalelength in edge-on and face-on samples. **(3)** It is not clear that in the study of truncations in face-on systems by Pohlen & Trujillo (2006) one is consistently deriving the same features as in edge-on galaxies. **(4)** In particular the lack of a correlation of truncation radius (and scalelength) with rotation velocity needs clarification; is this due to sample peculiarities or to the deprojection method?

3. Truncations and warps

Warps in the HI in external galaxies are most readily observed in edge-on systems as NGC 5907 (Sancisi 1976). NGC 5907 has a clear and sharp truncation (van der Kruit & Searle 1982) in its stellar disk at the same radius where the warp starts. The “prodigious warp” in NGC 4013 (Bottema et al. 1987; Bottema 1996) is very symmetric and starts suddenly near the end of the optical disk. Inside the warp the stellar disk and HI-layer are exceedingly flat. The stellar disk has a clear truncation (van der Kruit & Searle 1982). The three-dimensional analysis by Bottema confirms that in deprojection the warp starts very close to the truncation radius.

NGC 628 is almost completely face-on. The HI-velocity field displays a complicated pattern; in the tilted-ring model the rings actually go through the plane of the sky (Shostak & van der Kruit 1984). After subtraction of this rotation field the residuals show that systematic vertical motions in the gas are less than a few km/s, indicating again that the disk is extremely flat. The radial luminosity profiles (van der Kruit 1988) show evidence for a truncation, which again coincides with the onset of the warp.

So we see that, stellar disks and their accompanying HI-layers are extremely flat (except near the edges where sometimes minor optical warps are found) and HI-warps often start suddenly at about the truncation radius of the stellar disk (see also van der Kruit 2001).

In his Ph.D. thesis García-Ruiz (see García-Ruiz et al. 2002) presented HI observations of a sample of edge-on galaxies. His sample consisted of 26 edge-on galaxies of which at least 20 show evidence for an HI warp. Unfortunately, the optical surface photometry could not be calibrated. In a recent paper (van der Kruit 2007), I investigated whether the Sloan Digital Sky Survey (SDSS) can be used to see if there are truncations in this sample and if so, where the warps start with respect to these. In Fig. 5 I show two examples: UGC 7774 and UGC 6126 both have truncations; in UGC 7774 the HI-warp starts on the sky at R_{\max} while in UGC 6126 as at a radius inside R_{\max} . The observed distribution of the ratio R_{warp}/R_{\max} in the sample is statistically consistent with that for a random distribution of viewing angles in the situation, where *all* warps start at about $1.1 R_{\max}$. HI-warps and truncations therefore seem related.

The **properties of HI-warps** have been described by Briggs (1990) in the form of a set of rules of behaviour; with subsequent information we can summarize the most important properties as follows (for a more extended discussion

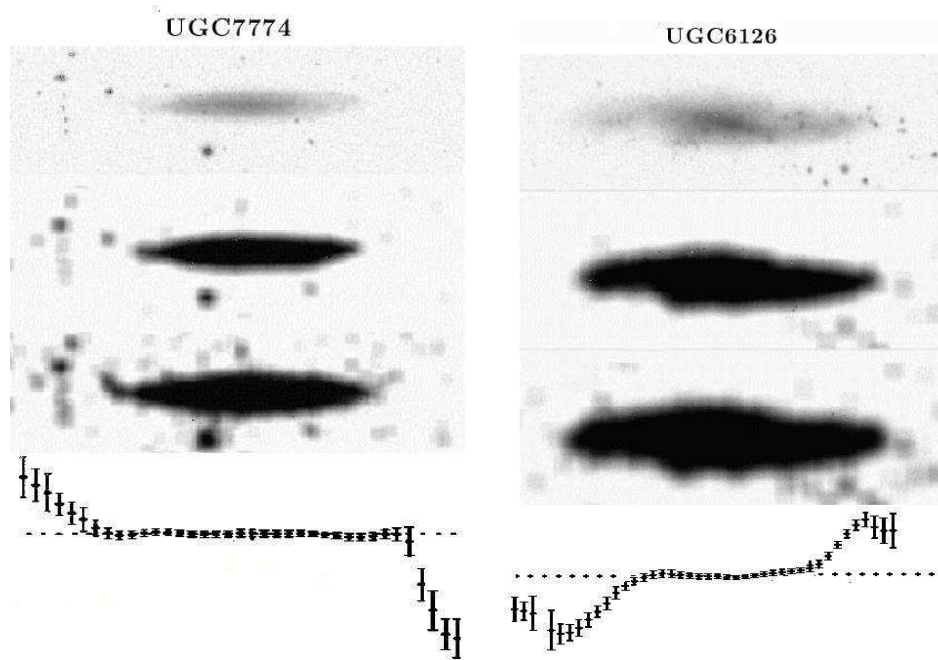


Figure 5. UGC 7774 and UGC 6126 (from van der Kruit 2007).

see van der Kruit, 2007):

- * All galaxies with HI extending beyond their optical disk have warps (García-Ruiz et al. 2002).
- * Many galaxies have relatively sharp truncations in their stellar disks.
- * 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” (Briggs 1990).

This leads to the following features of a possible formation scenario (van der Kruit 1987, 2001, 2007): **(1)** The inner disk (mostly stars) and the warped outer disk (mostly HI) are distinct components. **(2)** These probably have distinct formation histories and formed during different epochs. **(3)** Inner disks form initially and settle as rigid, flat structures with well-defined boundaries (truncations) corresponding to a maximum in the specific angular momentum distribution. **(4)** If the initial distribution resembles a Mestel sphere and if the collapse occurs with approximate conservation of specific angular momentum truncated, exponential disks result automatically. **(5)** HI-warps result from later infall of gas with a different orientation of angular momentum. **(6)** 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.

4. 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_{\max} with V_{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, involving modest redistribution of angular momentum.
- Stellar disks and their accompanying gas-layers are extremely 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.

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