STELLAR DISK TRUNCATIONS: WHERE DO WE STAND?

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Abstract
In the light of several recent developments we revisit the phenomenon of galactic stellar disk truncations. Even 25 years since the first paper on outer breaks in the radial light profiles of spiral galaxies, their origin is still unclear. The two most promising explanations are that these 'outer edges' either trace the maximum angular momentum during the galaxy formation epoch, or are associated with global star formation thresholds. Depending on their true physical nature, these outer edges may represent an improved size characteristic (e.g., as compared to $D_{25}$) and might contain fossil evidence imprinted by the galaxy formation and evolutionary history. We will address several observational aspects of disk truncations: their existence, not only in normal HSB galaxies, but also in LSB and even dwarf galaxies; their detailed shape, not sharp cut-offs as thought before, but in fact demarcating the start of a region with a steeper exponential distribution of starlight; their possible association with bars; as well as problems related to the line-of-sight integration for edge-on galaxies (the main targets for truncation searches so far). Taken together, these observations currently favour the star-formation threshold model, but more work is necessary to implement the truncations as adequate parameters characterising galactic disks.

1. Introduction

The structure of galactic disks is of fundamental importance for observationally addressing the formation and evolution of spiral galaxies. By measuring scalelengths for galaxy samples at different redshifts, it is for example possible to directly address the evolution of galactic disks using the scalelength as a tracer of their sizes (e.g. Labbé et al. 2003). To a first approximation, the radial light distribution of disks is well described by an exponential decline (Freeman 1970). However, for 25 years (since van der Kruit 1979), we have know that this exponential light distribution does not extend to arbitrarily large radii. Early, deep imaging using photographic plates showed that the disks are
radially truncated at the outer parts (Fig.1). While truncations were difficult to measure at that time – still true today for deriving their exact shapes – it has become progressively easier to detect these outer edges with modern CCD equipment. In the optical they occur at galactocentric distances of roughly 2-6 exponential scalelengths (cf. next Sect.). Truncations could be used as an additional, intrinsic parameter measuring the total size of galactic disks (maybe replacing the widely used, but purely arbitrary \( D_{25} \) definition), and truncations may be linked to the formation and evolution of disk galaxies in general. Despite the fact that they have been known for so long, we do not have a secure understanding of the origin for these outer edges, so their application as a fundamental disk characteristic is not yet possible. In this overview we will summarise what is currently known about truncations and describe the quest to unveil their true origin.

2. Where are normal galaxies truncated?

To understand their origin and use them as characteristic galaxy parameters (e.g. in comparative studies of different galaxy samples), one has to empirically establish where ‘normal disks’ are typically truncated – conventionally expressed in terms of radial scalelength – and what this truncation looks like.

The edge-on view

In their seminal series of papers on the 3-D light distribution in edge-on galaxies, van der Kruit & Searle (e.g. 1981a, 1981b) measured the ratio of truncation radius (\( R_{tr} \)) to radial scalelength (\( h \)) as \( 4.2 \pm 0.6 \) for a sample of seven nearby, large galaxies using photographic plates. They found that stellar disks have “rather sharp edges”, justifying the terms cut-off and truncation they used to describe them. Barteldrees & Dettmar (1994) collected more sensitive CCD images for a much larger sample of 27 edge-on galaxies – later reanalysed and slightly enlarged by Pohlen et al. (2000a) – finding significantly lower ratios of \( R_{tr}/h \), down to \( 2.9 \pm 0.7 \) in the latter study. The Groningen group followed with their CCD survey providing a mean ratio of \( 3.8 \pm 1.0 \) for a pilot sample of four galaxies (de Grijs et al. 2001). This lies in between the former two extremes, but clearly confirms the explicitly larger scatter observed by Pohlen et al. (2000a) compared to van der Kruit & Searle (1981b). Since line-of-sight (LOS) integration makes edge-on galaxies ideal candidates to search for truncations, Pohlen (2001) obtained new data, trying to finally settle the true nature of the truncations by using significantly deeper exposures and selecting objects as undisturbed as possible. This study showed without doubt that the previously used concept of a sharp truncation does not really hold, as already suggested in de Grijs et al. (2001). It is just possible to fit a sharply truncated model to this new data set (cf. Fig.1a): Pohlen (2001) derived a value of
Figure 1. (a) Left panel: Edge-on view: Radial surface brightness profiles (solid lines) of the edge-on galaxy NGC 522 together with the best fitting sharply-truncated model (dashed line) (b) Right panel: Face-on view: The azimuthally averaged radial surface brightness profile of the face-on galaxy NGC 5923 (solid line). In addition to the inner part (<8 arcsec) dominated by the bulge component an inner exponential slope (inner dotted line) is clearly visible out to the break radius at $R_{br} = 54''$. Followed by another outer exponential part (outer dotted line).

$R_{tr}/h = 3.5 \pm 0.8$ using 56 galaxies, which is similar to the values of $3.6 \pm 0.6$ from the full analysis of 20 galaxies from the Groningen CCD survey (Kregel et al. 2002). However, it has become clear that the radial profiles are far better described by a two-slope, or broken exponential structure, characterised by inner and outer scalelengths and a well-defined break radius. The deepest data show that LOS integration – a fairy godmother for detecting truncations – is at the same time the major drawback in analysing them in detail (Pohlen 2001). Since disks are only empirically described by an exponential – typically over at most a few scalelengths – the edge-on geometry of such a two-slope disk, with additional dust obscuring the major axis, complicates an already delicate fitting process. Edge-on, there are always uncertainties in where to mark the break radius (cf. Kregel et al. 2002), and in particular the calculation of the true, unprojected scalelength is heavily model dependent. Within a sharply truncated model used by e.g. Pohlen et al. (2000b) there is a strong coupling between the two parameters $R_{tr}$ and $h$. However, fitting an infinite exponential model – excluding the truncation region – does not really solve the problem, especially for galaxies which exhibit an early break (in terms of scalelength) and a steep outer decline. The LOS integration will distribute the measured light along the assumed uniformly exponential decline so the best determined fitting scalelength will be systematically too small (e.g. Pohlen et al. 2004). A simpler approach is that of Pohlen (2001), who avoided 3D, LOS issues by fitting the observed profile with a 1-D, two-slope model, finding $R_{tr}/h_{in} = 2.5 \pm 0.8$ from 37 galaxies. However, the fitted scalelengths in this case are not necessarily the intrinsic scalelengths, both because dust extinction increases the
measured scalelength and because the scalelength of a 1D fit is larger than the intrinsic scalelength by as much as 20% (e.g., de Grijs 1997).

The face-on view

The only way to settle the question of where the breaks in the radial profiles really occur is to go back to face-on galaxies as done earlier by van der Kruit (1988). Therefore, Pohlen et al. (2002) took deep, carefully flatfielded exposures of three face-on galaxies. The face-on geometry is practically independent of possible LOS effects caused by an integration across the multicomponent disk and much less affected by dust. These data quantitatively establish the smooth truncation behaviour of the radial surface brightness profiles, which is best described by a two-slope or broken exponential model, characterised by inner $h_{\text{in}}$ and outer $h_{\text{out}}$ exponential scalelengths separated at a relatively well defined break radius $R_{\text{br}}$ (cf. Fig.1b). The mean value for the distance independent ratio of break radius to inner scalelength – which marks the start of the truncation region – is $R_{\text{br}}/h_{\text{in}} = 3.9 \pm 0.7$ for the three galaxies. This value is significantly larger than the value for the edge-on sample, but this is expected given the systematic errors in the scalelength measurement in the edge-on case described above. It is slightly lower compared to $R_{\text{tr}}/h = 4.5 \pm 1.0$ for the 16 face-on galaxies obtained by van der Kruit (1988). This small shift could be due to the different methods used to derive the truncation – only estimated from isophote maps by van der Kruit (1988) – or the sample sizes and selections.

The combined view

In summary, the radial profiles show a two-slope or broken exponential behaviour with an inner and outer disk separated by a rather sharp break radius at $2.5 \lesssim R_{\text{br}}/h_{\text{in}} \lesssim 5.8$, taking the mean value from the three face-on galaxies of Pohlen et al. (2002) and the scatter from the larger edge-on sample of Pohlen (2001). However, it is clear that truncations – seen in different data sets, using different methods, and analysed by different groups – are real, in contrast to the recent claim of Narayan & Jog (2003). It is not a matter of “questioning their very existence”, but rather of determining the shape of the profiles beyond the break radius, which is admittedly still difficult to measure and a “puzzle” to explain.

3. Are all disk galaxies truncated?

The data of Pohlen (2001) suggest that a very high fraction –more than 79%– of mostly late-type edge-on disks are truncated. The remaining galaxies are either still disturbed (despite the careful selection), show an additional major structure not accounted for in a single component disk – such as outer envelopes or a strong bar –, or (in one case) have S/N that is too low. Kregel
et al. (2002) (see also Kregel 2003) support a rather high frequency of radial truncation features for a similar late-type sample of 34 edge-on galaxies. They find successful truncation fits for 20 galaxies (59%), whereas most of the other galaxies are rejected for technical reasons such as superimposed foreground stars or low S/N. The latter is the main problem of this sample in respect to truncations yielding only lower limits of typically \( R_{tr}/h > 4.5 \) for the other galaxies and just two cases of \( R_{tr}/h \gtrsim 6.0 \). However, just recently Erwin et al. (2004), analysing a large sample of intermediately inclined, early-type galaxies, found seven barred galaxies without measured truncations beyond six scalelengths. Although the edge-on samples certainly also contain barred galaxies, we may ask if only barred galaxies (sometimes) lack truncations. It is true that the detailed studies by Barton & Thompson (1997) and Weiner et al. (2001), which showed disks without truncation extending to at least seven and ten scalelengths, respectively, dealt with two strongly barred face-on galaxies. But the large collection of surface brightness profiles for unbarred or only weakly barred Sb–Sc galaxies by Courteau (1996) shows several cases of profiles which extend to at least six scalelengths without truncation, and the sample of Erwin et al. (2004) also includes one unbarred Sa galaxy (UGC 3580) with \( R_{tr}/h \gtrsim 5.8 \). It is still puzzling why the large edge-on samples – which have the advantage of LOS integration – are missing many of the “untruncated” galaxies (or galaxies with truncations beyond six scalelengths) seen in face-on samples. From the few late-type, face-ons in Pohlen et al. (2002) and the large collection of early-type, face-ons in Erwin et al. (2004) we know that azimuthal averaging does not play a significant role in smoothing out truncations. If untruncated disks really do exist, then models which attempt to explain truncations also need to explain why some disks are not truncated.

### 4. What is the origin of truncations?

Despite the recent success in disentangling where the disks are truly truncated, the nature of galactic disk truncations is far from understood and their place in theories of disk galaxy formation is still under debate. The proposed hypotheses span a rather wide range of possibilities, though there are clearly two favoured explanation: the **collapse model** and the **threshold model**. Van der Kruit (1987) deduced a direct connection to the galaxy formation process describing the truncations as remnants from the early collapse. The truncation reflects here the maximum angular momentum of the protogalaxy, which is completely independent of the hierarchical merging history. On the other hand, Kennicutt (1989) following Toomre (1964) has suggested a dynamical critical star-formation threshold (\( \Sigma_c \)) – recently addressed in a different version by Schaye (2004) – for thin, rotating, isothermal gas disks. If this persists over sufficient time it should produce a visible turnover or truncation in the
observed stellar luminosity profile at that radius. Here the truncation radius corresponds to the radial position where $\Sigma_{\text{gas}}(R) = \Sigma_c$. More recently, van den Bosch (2001) combined the collapse and threshold models. While there is a truncation of the cold gas which reflects the maximum specific angular momentum of the baryonic mass that has cooled, the truncation radius of the stars reflects the presence of a star-formation threshold. Alternatively, Zhang & Wyse (2000) and Ferguson & Clark (2001) have presented evolutionary scenarios – typified as viscous evolution models – which show features surprisingly comparable to the observed two-slope structure. However, according to Ferguson & Clark (2001) the breaks just reflect the initial conditions in the gas and tend to be smeared out while the galaxy evolves with time. Battaner et al. (2002) have proposed a connection with large scale galactic magnetic fields. This approach seems controversial, since it also explains flat rotation curves without dark matter; nevertheless, it is able to explain e.g. possible $R_{tr}/h$ variations with morphological type or rotational velocity. The formation of a truncated stellar disk by tidal interaction, although appealing, is in contradiction to the radial spreading shown by Quinn et al. (1993) in their numerical N-body simulations of satellite mergers. However, we are still missing an up-to-date N-body+SPH (stars and gas) simulation addressing a possible connection between truncations and interaction.

5. Can observations decide yet?

The star-formation threshold models of Schaye (2004) and van den Bosch (2001) both predict a correlation of the ratio $R_{tr}/h$ with the central surface brightness. Low-surface brightness galaxies should have lower values, as indeed indicated by current observations (cf. Fig.2a or Kregel 2003). The collapse model does not account for such a correlation since it predicts instead a fixed value for all galaxies, allowing for only very small scatter. According to the threshold models a similar trend should be observed in relation to the mass of the galaxy. Low-mass systems (characterised e.g. by smaller rotational velocities) should have smaller values for the ratio of truncation radius to radial scalelength, as indicated by Pohlen (2001) (cf. Fig.2b). Additional support for a correlation with mass comes from recent work on nearby dwarf galaxies. Hunter (2002), Simon et al. (2003), and Hidalgo et al. (2003) all find similar two-slope profiles with rather low values for $R_{tr}/h_{\text{in}}$. The currently available large edge-on samples do not sufficiently cover the Hubble sequence to address the prediction by van den Bosch (2001) that early-type, bulge dominated galaxies (Sa to S0) should have $R_{tr}/h \lesssim 2$. However, in the large sample of moderately inclined, early-type, barred galaxies of Erwin et al. (2004), most galaxies do not follow this relation. Only a small subset does, but these truncations are far better described as bar-related OLR breaks (cf. Sect.6). This
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Figure 2. (a) Left panel: Ratio of break radius to inner scalelength ($R_{br}/h_{ini}$) versus face-on central surface brightness. Crosses: edge-ons by Pohlen (2001). Squares: face-ons by Pohlen et al. (2002). Dashed line: threshold prediction by Schaye (2004) according to Kregel (2003) (b) Right panel: $R_{br}/h_{ini}$ versus maximum rotational velocity $v_{rot}$. Crosses: edge-ons by Pohlen (2001). Circles: two face-on galaxies with known $v_{rot}$ from the sample of Pohlen et al. (2002) shifted to account for the mean systematic error of the two samples (cf. Sect.2).

failure of the promising threshold model of van den Bosch (2001) could be due to its rather general implementation of the bulge formation process. Kennicutt (1989) (see also Martin & Kennicutt 2001), measuring radial Hα distributions, observed that the star-formation rate drops abruptly at a finite radius. Unfortunately only a few galaxies with both Hα and optical breaks are currently available for testing the one-to-one correlation expected in a simple threshold scenario. Current data does indicate such a correlation (cf. Fig.3a or Hunter 2002), while beyond the break the decline in the Hα luminosity seems to be more rapid than the stellar one. We know that disk galaxies have radial colour gradients: the disk gets bluer towards the edge (de Jong 1996). This implies that disks get radially younger – arguing for an inside-out formation scenario – in the sense that their inner regions are older and more metal rich than their outer regions (Bell & de Jong 2000). However, this does not explain the truncation radius as the radius to which the disk has now grown (e.g. Larson 1976), since the stars beyond the break are indeed younger but still many Gyrs old. This is confirmed by Davidge (2003), who studied the resolved stellar populations of NGC 2403 and found that while young stars are restricted to the inner parts, AGB stars observed in the outer parts suggested that star-formation has occurred there during intermediate epochs of 1 Gyr or more. The measured B- and R-band profiles of the face-on galaxy NGC 5923 – which trace the combined star-formation history – indicate that the radial blueing extends only out to the optical break, which is at the same radius in both bands (cf. Fig.3b). Outside the break the outer disk has a constant blue colour $(B - R) = 0.9$, which argues for either a single population or a coherent star-formation his-
Figure 3. (a) Left panel: Comparison of R-band major axis profile (6.2′ vertically averaged) of UGC 7321 and a scaled version of the continuum subtracted Hα. (b) Right panel: The B- and R-band azimuthally averaged radial surface brightness profiles of the face-on galaxy NGC 5923.

NIR data may help to determine the question if the old stellar population – tracing the mass of the galaxy – changes across the break. Data by Florido et al. (2001) show for the first time that truncations are also present in NIR images and that they are rather sharp. It turned out that these truncations are significantly smaller compared to the optical ones and it would be interesting to confirm these observations independently (cf. Pohlen 2001).

6. Are bars an alternative solution?

Many barred galaxies possess rings in their outer disk produced by the bar’s outer Lindblad resonance (OLR). While some of these rings are seen in radial profiles as mere bumps on an underlying exponential disk, Erwin et al. (2004) found that a large fraction of their barred, early-type galaxies exhibit breaks associated with the OLR. Many of these OLR breaks resemble the classical truncations described above, but located further inside. This implies that the bar is able to re-shape the initial gas disk (maybe replenished by later infall) out to substantial radii ($\approx 1–2 \times h_{\text{in}} \approx 2 \times \text{radius of bar}$). Without additional data it is not yet clear if these OLR breaks also occur in more late-type galaxies – known to have smaller and weaker bars – thus providing a true alternative to the now favoured threshold theory (Erwin et al. 2004). However, the three clearly unbarred face-on Sbc–Sc galaxies of Pohlen et al. (2002) argue against OLR breaks as the sole explanation for truncations, if one does not assume that these galaxies once had bars which are now dissolved. The intriguing existence of barred but untruncated galaxies (cf. Sect.3) implies that bars may also prevent truncations in some cases.
7. Any open questions?

The smooth nature of truncations clearly shows that there are stars outside the break radius. While the previously considered sharp truncations would agree nicely with the threshold model, a simple critical density does not account for the observed two-slope structure. There are two possible explanations for these stars beyond the break radius. They could be either born in situ – out of an initial, maybe viscously redistributed, and already replenished gas disk – or they are stars from the inner disk which have migrated outwards in a kind of diffusion process. Ferguson et al. (1998) already showed for a couple of galaxies that there is local star-formation at large galactocentric distances, probably beyond a break radius, supporting the former possibility. However, both approaches still have to explain why the inner and outer disk regions are produced with different, yet still exponential, slopes, why the transition zone appears to be rather sharp, and – even more challenging – why the outer disk is so large: Pohlen et al. (2002) showed for the face-on galaxies that the break radius is at $R_{br} = \frac{2}{3} R_{lmp}$ using the last measured point ($R_{lmp}$) as a reference. In the case of the Milky-Way ($R_{lmp} \geq 21$ kpc) this implies an inner disk of 14 kpc and an outer disk of at least 7 kpc extra radius! This is significantly larger than the usually assumed values of $\approx 1$ kpc previously deduced for a sharp truncation. According to Pérez-Martin (this volume) there seems to be a trend of galaxies being truncated earlier (in terms of $h$) at higher redshift (consistent with Tamm & Tenjes 2003). So far, none of the described models has addressed such an interesting evolution with redshift.

8. Summary and Outlook

Finally, we want to emphasize that the observed radial profiles show rather sharp break radii. However, they are not sharply truncated – in the sense of an outer radius beyond which no further stars can be found – as is often assumed in the literature. Despite the success of recent studies of the structural parameters, a medium-deep survey of a well selected sample of local, intermediate inclination to face-on disk galaxies along the Hubble sequence is still necessary, to provide ultimately the reference value of $R_{tr}/h$. The star-formation threshold model seems to be the most promising hypothesis to explain the presence of truncations so far. Although less direct than the collapse model – which directly relates observed truncations to initial conditions – van den Bosch’s (2001) model showed how to implement such a star-formation threshold in a collapse model which is able to trace the evolutionary picture. We are still working on additional observational support, such as more H$\alpha$-to-optical break comparisons, detailed measurements of the atomic and molecular gas densities out to the break radius, and measurements of the stellar kinematics and population differences inside and outside the break.
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