Radial truncations in stellar discs in galaxies

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ABSTRACT
We discuss the possible origin of the radial truncations in stellar discs, using measurements that we presented in an earlier paper (Kregel, van der Kruit & de Grijs 2002). A tentative correlation is found with the de-projected face-on central surface brightness; lower surface brightness discs tend to have a smaller truncation radius in units of scalelength. This and our earlier finding that in smaller spirals the truncation tends to occur at a larger number of scalelengths are best reproduced when the truncation is caused by a constant gas density threshold on star formation.

Key words: galaxies: fundamental parameters – galaxies: spiral – galaxies: structure

1 INTRODUCTION
Stellar discs have a finite size. In the extreme outer parts the stellar light distribution diminishes more steeply than the exponential decline over the main disc and drops to low values beyond the so-called truncation radius \( R_{\text{max}} \) (van der Kruit 1979, van der Kruit & Searle 1981, 1982, hereafter KS1–3; Pohlen et al. 2000; Schwarzkopf & Dettmar 2000; de Grijs, Kregel, & Wesson 2001, hereafter GKW; Florido et al. 2001). This truncation or cut-off of the disc light is often directly visible in contour maps of edge-on spirals and usually occurs at a radius of 3 to 5 disc scalelengths (van der Kruit 2001a), although stellar discs that extend to a much larger number of scalelengths are certainly known to exist (e.g. Weiner et al. 2001b). The truncation is most easily found in edge-on spirals because of the line-of-sight projection and the associated higher surface brightness.

In less inclined spirals, for which azimuthally averaged radial light profiles are routinely studied, the non-axisymmetric component (e.g. spiral structure, lopsidedness) can smooth out a truncation present in the old disc. This effect was first noted by van der Kruit (1988). For 16 face-on spirals, of which 15 did not show any sign of a truncation in the azimuthally averaged light profile, he found that the three outermost isophotes were much more closely spaced than the inner ones, providing clear evidence for the truncation. The Milky Way disc probably also revealed truncations in the Local Group galaxies NGC 2403 (Davidge 2003) and NGC 3109 (Demers et al. 2003).

The origin of the truncation of the stellar disc is still unclear and could possibly result from a number of physical scenarios (van der Kruit 2001a; Freeman 2002). For example, if there has been no major redistribution of the disc angular momentum during its formation and evolution, the truncation may reflect the maximum specific angular momentum of the protogalaxy (van der Kruit 1987). This would imply that the H\textsc{I} extending beyond the stellar disc (e.g. Broeils & Rhee 1997) has been accreted, and that the truncation is associated with a small drop in the rotation curve (KS3; Bottema 1996). Another interesting possibility is that the truncation corresponds to the radius at which the gas density drops below a threshold density necessary for star formation (Fall & Efstathiou 1980; KS3; Kennicutt 1983; Schaye 2004).

In Kregel, van der Kruit & de Grijs (2002, hereafter KKG) we fitted truncation radii to the photometry of 34 edge-on galaxies from the sample of de Grijs (1997, 1998). The selection criteria and properties of this sample are summarized in KKG (sect. 2 and table 1). The sample covers a large range in rotation velocity (\( v_{\text{max}} = 50–400\) km s\(^{-1}\)) and is dominated by spirals of intermediate- to late-type. Of the 34 galaxies we found that at least 20 have truncated discs. The truncation radii \( R_{\text{max}} \) have been listed in Table 5 in KKG. Here we further compare the observed truncation radii to those predicted by the scenarios proposed for the origin of the truncation, and specifically address the behaviour with disc surface brightness (see also Kregel 2003).
2 THE TRUNCATION RADIUS VERSUS DISC PARAMETERS

We show the distribution of $R_{\text{max}}/h_R$ versus scalelength in Fig. 1a. For those galaxies for which no truncation was found, the lower limit is shown (arrows). Figure 1 appears to show a subtle increase in $R_{\text{max}}/h_R$ towards small scalelengths; the average ratio for the spirals with $h_R < 4$ kpc is 4.4, more than one standard deviation higher than that of the entire sample. This increase of $R_{\text{max}}/h_R$ may be related to its decrease found at very large scalelengths by Pohlen et al. (2004). However, the reality of this feature is not entirely clear considering the modest sample size and low surface brightness. We are, for example, still missing small low surface brightness galaxies, which may have entirely different $R_{\text{max}}/h_R$. While our view of the distribution of $R_{\text{max}}/h_R$ is certainly obscured by this selection effect, additional information can be obtained from face-on samples. We have estimated a lower limit to $R_{\text{max}}/h_R$ for the spirals in the face-on sample of de Jong & van der Kruit (1994), a sample which is dominated by spirals of small scalelength. By taking the lowest contour in their $R$-band contour plots as a lower limit to $R_{\text{max}}$, we find an average ($R_{\text{max}}/h_R$)$_{\text{min}} = 4.0\pm1.1$ ($1\sigma$). This lower limit and the tentative increase of $R_{\text{max}}/h_R$ towards small scalelength spirals suggest that the ratio of truncation radius to disc scalelength in small scalelength nearby spirals is at least four.

Figure 1b shows the dimensionless truncation radius versus the de-projected face-on central surface brightness (corrected for Galactic extinction as in de Grijs 1998). The ratio $R_{\text{max}}/h_R$ appears to be correlated with surface brightness in the sense that lower surface brightness discs tend to truncate at a smaller number of scalelengths. A Spearman rank correlation test appears conclusive, yielding a correlation coefficient of 0.61 (or a confidence level greater than 99%). However, the errors are substantial in many cases and not entirely random, so that the test could have given a false positive result. Note that the face-on surface brightnesses are probably underestimated, by $\sim 0.7$ mag according to a comparison between the Tully-Fisher relations of edge-on and face-on spirals (Kregel, van der Kruit & Freeman 2004, hereafter KKF). The large lower limits for ESO 340-G08 and ESO 555-G36 are puzzling. The discs of these spirals appear to be far more extended than the norm.

Figures 1a & b combined suggest that in small scalelength, high surface brightness spirals the truncation occurs at at least four scalelengths. This is important, because small spirals ($h_R \lesssim 4$ kpc) are the most numerous in the local Universe (van der Kruit 1987; de Jong & Lacey 2000, KKG). As another corollary, the range in face-on surface brightness among spirals is narrower at $R_{\text{max}}$ than at the disc centre. If the discs in the current sample are exponential out to $R_{\text{max}}$ then the distribution of $R$-band face-on surface brightnesses at $R_{\text{max}}$ has an average of 25.3 mag arcsec$^{-2}$ and a 1\sigma scatter of 0.6 mag arcsec$^{-2}$. This dispersion is considerably smaller than the 1.1 mag arcsec$^{-2}$ dispersion in the central surface brightness. This also implies that in the face-on view, the truncation is just as easily (or laboriously) detected in LSB as in HSB spirals.

3 COMPARISON WITH HYPOTHESES FOR THE ORIGIN OF THE TRUNCATIONS

We can compare the observed trends to the predictions of the analytical collapse model of disc galaxy formation (Fall & Efstathiou 1980; Gunn 1982; Dalcanton, Spergel & Summers 1997, hereafter DSS97). If protogalaxies are relatively sharp-edged, then the collapse theory also predicts the outermost radius of the baryonic disc (van der Kruit 1987). This radius corresponds to the material with the highest specific angular momentum in

Figure 1. (a) – $R_{\text{max}}/h_R$ versus disc scalelength. The arrows indicate lower limits for galaxies for which no $R_{\text{max}}$ could be determined. The cross-hatched region shows the prediction of the collapse model for disc galaxy formation (see text). The dashed lines show the predicted threshold radii for star formation for disc masses of, from bottom to top, $7.5 \times 10^9$, $5 \times 7.5 \times 10^9$ and $25 \times 7.5 \times 10^9$ M$_{\odot}$. (b) – $R_{\text{max}}/h_R$ versus face-on central surface brightness in the $I$-band. The arrows and the cross-hatched region is as in (a). The dashed line shows the constant star-formation threshold prediction. The shifted dotted line is obtained when allowing for an underestimation of the surface brightnesses by 0.7 mag (see text).
the protogalaxy. To quantify this prediction we calculated model surface density profiles using the method of DSS97 for a range in spin parameter and total mass of the protogalaxy. We assume a constant baryonic mass fraction \( F = 0.10 \) and a constant efficiency for turning the baryons into stars over the age of the disc at \( (M/L)_\text{disc} = 2 \) (see KKF). The scalelengths were derived using a method similar to the ‘marking-the-disc’ method of Freeman [1971], and the outermost radii were obtained by taking the radius at which the density drops to zero. The result is indicated by the cross-hatched region in Figs. I.

In the collapse theory, both the outermost radius and the scalelength of the baryonic proto-disc increase with the mass and angular momentum of the protogalaxy such that their ratio remains approximately constant at 3–4. Taking a different or non-constant baryon mass fraction does not significantly change this result. The predicted \( R_{\text{max}}/h_R \) is slightly smaller than the ratio of 4.5 predicted by van der Kruit [1987] based on a comparison of the angular momentum distribution of an exponential disc with that of a uniformly rotating, uniform sphere with \( \lambda = 0.07 \). Although the prediction of the collapse model roughly coincides with the average observed \( R_{\text{max}}/h_R \), it cannot explain the existence of discs which extend to a relatively large or a small number of scalelengths. In particular, it does not predict an increase of \( R_{\text{max}}/h_R \) toward small scalelengths (Fig. I), or a decrease towards low surface brightness discs (Fig. I). Taking a different halo density profile and/or angular momentum profile could change the value of \( R_{\text{max}}/h_R \), but not its constancy. Including additional prescriptions for mass accretion, star formation and supernova feedback can lead to \( R_{\text{max}}/h_R \) ratios that do change as a function of central surface brightness, but with the opposite sign (van den Bosch [2001]). Perhaps taking a range in angular momentum profiles, as suggested by N-body simulations in the ΛCDM cosmology (Bullock et al. 2001a), or re-distributing the angular momentum during and/or after the collapse could solve the discrepancy.

Alternatively, the stellar disc truncation may be caused by the inhibition of widespread star formation below a critical gas surface density (Fall & Efstathiou [1980; KS3; Kennicutt [1989]), if the corresponding critical radius is approximately constant over time. This star formation threshold is suspected to be related to the stability of the gas disc. Recently, Schaye [2004] made a prediction for the threshold radius based on simulations of the thermal and ionization structure of the gaseous discs assembled in the galaxy formation model of Mo et al. [1998]. In these simulations the transition to the cold ISM phase is responsible for the onset of local gravitational instability that triggers star formation. This transition to the cold phase is independent of the shape of the rotation curve and occurs at a critical gas surface density, which for reasonable values of the gas fraction, turbulence, metallicity and the UV radiation intensity attains values in the range \( \Sigma_c \sim 3–10 \, M_\odot \, pc^{-2} \) (Schaye [2004]). For a disc with an exponential surface density profile, he finds:

\[
\frac{R_{\text{max}}}{h_R} = \ln \frac{M_{\text{disc}}}{2\pi h^2 R \Sigma_c},
\]

where \( M_{\text{disc}} \) is the disc mass (gas and stars) and \( h_R \) is the mass scalelength. It is easy to show that when the gas mass is negligible this prediction reduces to:

\[
\frac{R_{\text{max}}}{h_R} = \ln \frac{M_{\text{disc}}}{2\pi h^2 R \Sigma_c}.
\]

The predicted threshold radii according to Eqn. 1 are shown in Fig. I, for three disc masses and Schaye’s [2004] fiducial critical surface density \( \Sigma_c = 5.9 \, M_\odot \, pc^{-2} \) \( (\Sigma_{\text{HI}} = 5.6 \times 10^{20} \, cm^{-2}) \). For the adopted disc masses, the threshold model brackets the observations. Interestingly, the model predicts an increase in \( R_{\text{max}}/h_R \) towards small scalelengths. Discs with a higher central surface density form stars out to a larger radius in terms of scalelengths before reaching the critical density. Since, for constant total disc mass, a higher surface density disc has a smaller scalelength, it follows that smaller scalelength discs have larger \( R_{\text{max}}/h_R \). This anti-correlation, which is similar to the observed trend in the Pohlen et al. [2001a] sample (Schaye [2004]), is also in accordance with the present observations.

Motivated by the observation that the HI gas fraction in the galaxies is small (Kregel, van der Kruit & de Blok [2004], hereafter KKB), we show Eqn. 2 in Fig. I, assuming \( \Sigma_c = 5.9 \, M_\odot \, pc^{-2} \) and \( (M/L)_\star = 2 \) (constant among galaxies). Lower surface brightness discs are predicted to be less extended, with a slope in agreement with the observed trend. The match is better if we take into account that the inferred disc central surface brightnesses are fainter by about 0.7 magnitudes compared to their face-on counterparts (KKF). The scatter and outliers may be explained as being due to a non-constancy in \( \Sigma_c \), e.g., due to a varying UV radiation intensity or metallicity, or due to a variation of \( (M/L)_\star \). Altogether, the observations are consistent with a ‘critical surface brightness’ in the range \( \Sigma_c/(M/L)_\star = 1.5–4 \, L_{\odot, I} \, pc^{-2} \). Sining it differently, for \( \Sigma_c = 5.9 \, M_\odot \, pc^{-2} \) the stellar
mass-to-light ratio is \((M/L)_\odot = 4\)–1.5. The lower part of this range is reasonable, both from the perspective of stellar population synthesis and observations of the stellar velocity dispersions in galaxy discs (Bottema 1993).

Both models can also be compared to the truncation analysis performed by Pohlen (2001) in the V and the R bands (Fig. 4). Although obtained using a different method, these data show a trend very similar to our \(V\)-band result (Fig. 1) and to the star-formation threshold model (dotted line). Lower surface brightness discs tend to be less extended in terms of \(R_{\text{max}}\).

It has long been known that viscosity driven angular momentum re-distribution within a star-forming gas disc may drive the resulting stellar disc towards an exponential profile (Lin & Pringle 1987). Depending on the details of star formation, this process may yield a stellar disc with a well-defined edge that advances radially outward with time (Ferguson & Clarke 2001). Unfortunately, the theory has not yet been explicitly investigated with respect to this truncation radius. The theory of stochastic self-propagating star formation predicts \(R_{\text{max}}/R_E = 4\) (Seiden et al. 1984) for flat rotation curves. This prediction is similar to that of the collapse model, leading to the same difficulties of predicting no dependence on surface brightness.

4 CONCLUSIONS

At least 20 galaxies in our sample of 34 have truncated stellar discs, displaying a tight relation between disc scalelength and truncation radius. The stellar disc edge seems to occur at a larger number of scalelengths in galaxies with a smaller scalelength, in agreement with the decrease of \(R_{\text{max}}/R_E\) towards large scalelengths reported by Pohlen et al. (2000).

In addition, we observe a tentative correlation between the ratio \(R_{\text{max}}/R_E\) and the de-projected face-on central surface brightness of the disc. These observations appear to have two important implications. First, high surface brightness spirals with small scalelengths, which are the most numerous spirals in the local Universe (de Jong & Lacey 2000), have an \(R_{\text{max}}/R_E\) of at least four. Secondly, the face-on disc surface brightness at the truncation radius is roughly constant among galaxies.

The observed truncation radii were compared to the predictions of several theories proposed for its origin. The data are best reproduced by the constant star-formation threshold model for the truncation (Schaye 2004). In particular, this model is able to match the correlation between \(R_{\text{max}}/R_E\) and surface brightness for reasonable stellar mass-to-light ratios. The collapse model for disc galaxy formation (van der Kruit 1987; DSS97), in which the truncation corresponds to the maximum angular momentum in the protogalaxy before disc collapse with detailed conservation of angular momentum, provides a significantly poorer match to the observations. This model would require some amount of re-distribution of angular momentum during and/or after the collapse.
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