The outer disks of galaxies

Pohlen, M.; Trujillo, I.

Published in:
The Astrophysical Journal

Publication date:
2005

Citation for published version (APA):
Pohlen, M., & Trujillo, I. (2005). The outer disks of galaxies: "To be or not to be truncated?". The Astrophysical Journal, 626(2).

THE OUTER DISKS OF GALAXIES: “TO BE OR NOT TO BE TRUNCATED?”

Michael Pohlen[1] and Ignacio Trujillo[2]

[1]*Kapteyn Astronomical Institute, University of Groningen, The Netherlands*

[2]*Max–Planck–Institut für Astronomie, Heidelberg, Germany*

Abstract We have in recent years come to view the outer parts of galaxies as having vital clues about their formation and evolution. Here, we would like to briefly present our results from a complete sample of nearby, late-type, spiral galaxies, using data from the SDSS survey, especially focused on the stellar light distribution in the outer disk. Our study shows that only the minority of late-type galaxies show a classical, exponential Freeman Type I profile down to the noise limit, whereas the majority exhibit either downbending (stellar truncation as introduced 1979 by Piet van der Kruit) or upbending profiles.

1. Historical introduction

Why study outer disks? The structure of galactic disks is of fundamental importance for observationally addressing the formation and evolution of spiral galaxies. Especially the *outer edges* of disk galaxies are of interest, since substructure, the so called fossil evidence, is expected to be imprinted by the galaxy formation process. Recent formation and evolution scenarios suggest for example that galaxies continue to grow from the accretion and tidal disruption of satellite companions.

What is their shape? The general shape of the surface brightness profile of galactic disks is currently one of our favourite paradigms, namely a pure exponential disk. Its success is based solely on empirical evidence (albeit dating back now nearly 50 years) and has in fact never been fully physically motivated.

> In view of the great variety of structures among spirals ... there is good evidence, however, that at least in ordinary spirals the smoothed radial luminosity distribution is approximately exponential in the outer parts (de Vaucouleurs 1959)

Eleven years later the general nature of disks was finally settled by Ken Freeman in his 1970 paper.

> Almost every disklike galaxy with measured $I(R)$ shows an exponential disk ... and its origin is certainly a significant cosmogonic problem. (Freeman 1970)

However, only nine years later Piet van den Kruit indicated that the exponential nature does not hold to infinity, but

> [..] at the edges of the disk the decrease in apparent surface brightness is exceedingly steep. This sharp drop implies that galaxies do not retain their exponential light distribution to such faint levels. (van der Kruit 1979)

This marked the detection of truncations at a safe distance of $\sim\ 4.5$ times the radial scalelength, so the paradigm of the exponential disk was not in real danger at the time.

Where are they truncated? After van der Kruit and Searle's seminal papers about the structure of galactic disks (e.g. van der Kruit & Searle 1981), the matter of imperfectly exponential disks was rather ignored for some more ten years, until Barteldrees & Dettmar (1994) confirmed their existence using for the first time modern CCD equipment, but placed the cut-off closer to the center, for some galaxies at a disturbing close $<\ 3$ times the scalelength.
Finally starting from the year 2000 several groups (e.g. Pohlen et al. 2000, de Grijs et al. 2001, Florido et al. 2001, Kregel et al. 2002, Pohlen et al. 2002, or Erwin et al. 2005a) followed up the question of where the disks are truncated, how the shape of the profile in the very outer parts looks like, and if all disks have a truncation. For a recent review see Pohlen et al. (2004).
To keep a long story short our answer is that we know now that not all galaxies are truncated, but those which are, are now believed to be truncated 'early' (at $\sim 3h$), often abruptly (but not completely) and the profiles are best described as a broken exponential and so probably better called *breaks* than *cut-offs*. The prototypical break is recently observed for M 33 by Ferguson (this volume) using the star-count method as an independent approach compared to the so far purely surface photometric measurements. The currently favoured origin for these breaks are global star-formation thresholds as described by Martin & Kennicutt (2001) or Schaye (2004), although this does not explain the origin of the material beyond the break (see Pohlen et al. 2004).

What next? What we still need is a complete census of the outer disk structure in the local universe extending the work done by Courteau (1996) and de Jong (1996) including a detailed discussion of the light profile in the outer region to answer our famous question: "To be or not to be (truncated)?". This is now done and will be presented briefly here and later in detail in Pohlen & Trujillo (2005, in prep.) for late-type galaxies and in Erwin et al. (2005b, in prep.) for early-type galaxies.

2. Sample

We used the LEDA online catalogue (the richest, most complete and up-to-date catalogue with homogeneous parameters of galaxies for the largest available sample) to select our initial galaxy sample using the following selection criteria: $2.99 < T < 8.49$ (Sb-Sdm), $\log r_{25} < 0.301$, $v_{\rm vir} < 3250$ km/s, $|b2| > 20^\circ$, and $M_{\rm abs} < -18.4$ B-mag. This leaves us with an unbiased, volume limited sample of late-type, face-on ($i \lesssim 60\,{\rm deg}$), nearby (local) disk galaxies (avoiding the Milky Way). Our sample complements the CCD imaging sample of ~ 65 early-type SB0-SBb galaxies by Erwin et al. (2005b, in prep.). The actual data we use for our present study come from the Sloan Digital Sky Survey (SDSS, data release 2) providing images of $\sim 15\%$ (98/655) of the galaxies in our original LEDA sample.

3. Results

SDSS profiles: To convince the reader, and first of all ourselves, that SDSS images with a rather short exposure time of only $\sim$ 60s are indeed deep enough to trace the outer disk we compared for three galaxies SDSS images with deep surface photometry. The deep data is presented in Pohlen et al. (2002) and was obtained at the CAHA 2.2m telescope using CAFOS. The total exposure time of these images is about 3 hours reaching reliably down to $\mu_{\rm lim} = 27.2$ R-mag/sqarcsec. As shown in Fig.1 (for two of the galaxies) the agreement is astonishingly good, allowing us to safely use SDSS images to study the profile clearly beyond the break radius.

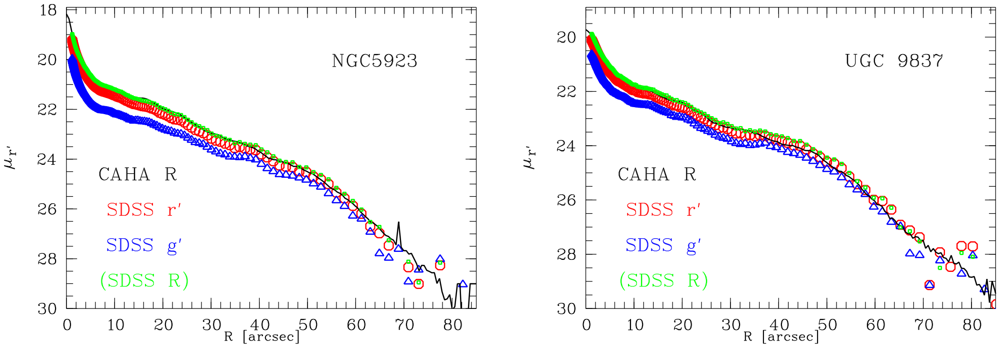

Figure 1. Comparison of the azimuthally averaged, radial surface brightness profiles from SDSS images with much deeper imaging by Pohlen et al. (2002). The small, green squares are produced by using the transformation to convert SDSS g' and r' into standard Johnson R band following Smith et al. (2002).

Classification: We classify each galaxy profile by eye according to the following nomenclature. If there is no indication for any obvious break in the profile the galaxy is classified as Type I following Freeman (1970). In the same sense, galaxies showing a profile better described as a broken exponential with a clear break and a *downbending*, steeper outer region are defined here as Type II:

> Type II has $I(R) < I_0 \exp(-\alpha R)$ in an interval $R_1 < R < R_2$ not far from the center. (Freeman 1970)

This definition includes the class of truncated galaxies shown by Pohlen et al. (2002). Although "not far from the center" may suggest to exclude truncated galaxies (where the break is at several radial scalelengths) from this class, thus following quote allows us to generalise Ken's definition:

> It is worth pointing out that for the [...] galaxies in which the Type II characteristic is most prominent [e.g. NGC 7793], the exponential disk begins outside the main region of the spiral-arm activity. (Freeman 1970)

Finally, following Erwin et al. (2005a), galaxies showing a broken exponential profile with a break, but followed by an *upbending*, shallower outer region, are called Type III. Three proto-typical cases are shown in Fig.2.

Frequencies and parameter distribution: The Type II class is split into several sub classes (discussed in detail by Pohlen & Trujillo, 2005, in prep.) but the majority, about $32.9\% \pm 5.1\%$ of the total sample, are what we call now *classical truncations* (Type CT), associated with those having a star formation threshold origin. An equal amount of galaxies (also 32.9%) are in fact *anti-truncated* and fall into the Type III class. Finally, only the minority ($15.3\% \pm 3.9\%$) of galaxies is barely consistent with being pure exponential disks of Type I.

We find indications for a trend with Hubble Type: Early-type galaxies (Sb-Sc) are more commonly Type III while Type CTs seem to be significantly more frequent in later types. Counting the neighbouring galaxies around each galaxy reveals the fact that Type III galaxies statistically prefer a high density, Type CT galaxies a low density environment. However, this relation is far from being clear-cut.

The break radius for galaxies with classical truncations, the ones discovered by Piet van der Kruit in 1979, happens in the r' band at $R_{\rm break} = 2.5 \pm 0.6\, h_{\rm inner}$ ranging between 1.4 and 4.2. Since we can follow the profile of the Type I galaxies down to $\sim 6-8$ times their scalelength, they seem to be genuinely untruncated galaxies.

While the scalelength varies with filter (being larger in g' compared to r') as known before, we do not find a systematic difference for the break radius. We do, however, find that the distribution of the surface brightness at the break

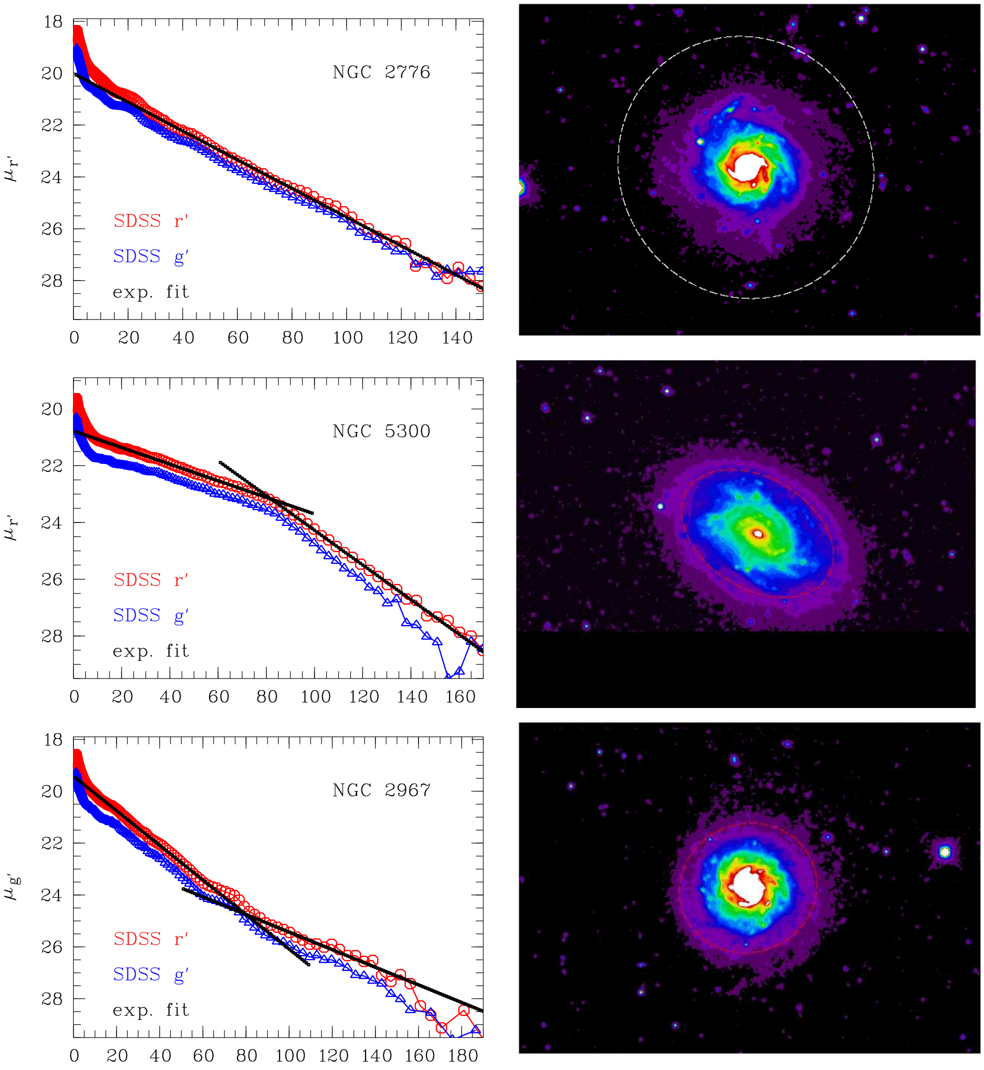

Figure 2. The three main disk types: Type I, Type CT, and Type III *(from top to bottom)*. Left column: Azimuthally averaged, radial (in units of $['']$) SDSS surface brightness profiles in the g' and r' band overlayed by r' band exponential fits to the individual regions: single disk; inner and outer disk. Right column: r' band images with the break radius marked as a red ellipse. The white ellipse for the first Type I galaxy corresponds to roughly the noise limit at $\sim\ 140''$.

radius $\mu_{\rm break}$ for galaxies with a classical truncation is peaked around a mean value. Together with the absence of a relation between $R_{\rm break}/h_{\rm inner}$ and mass (rotational velocity), this favours a star formation threshold scenario for its origin.

4. Stellar Disks truncations at high-z

Pérez (2004, and this volume) showed that it is possible to detect truncations even out to high redshift ($z \sim 1$). So we carefully defined a complete sample of high redshift galaxies (Trujillo & Pohlen, 2005) using the ACS data of the Hubble Ultra Deep Field. From the final sample of 36 galaxies, 21 show truncations. Now, using the position of the truncation as a direct estimator of the size of the stellar disk it becomes possible to outright observe inside-out growth of galactic disks comparing the ACS to our local SDSS sample. The results suggest that the radial position of the truncation has increased with cosmic time by $\sim 1-3$ kpc in the last ~ 8 Gyr indicating a small to moderate ($\sim 25\%$) inside-out growth of the disk galaxies since $z \sim 1$ (see Trujillo & Pohlen, 2005).

Acknowledgments

M.P. would like to thank Peter Erwin and John Beckman for their stimulating discussions and useful suggestions during this work. Part of this work was supported by a Marie Curie Intra-European Fellowship within the 6th European Community Framework Programme.

References

Barteldrees, A., & Dettmar, R.-J. 1994, A&AS, 103, 475

Courteau, S. 1996, ApJS, 103, 363

de Grijs, R., Kregel, M., & Wesson, K. H. 2001, MNRAS, 324, 1074

de Jong, R. S. 1996, A&A 313, 45

de Vaucouleurs, G. 1959, Handbuch der Physik, 53, 311

Erwin, P., Beckman, J. E., & Pohlen, M. 2005a, ApJ, 626, L81

Florido, E., Battaner, E., Guijarro, A., Garzón, F., & Jiménez-Vicente, J. 2001, A&A, 378, 82

Freeman K. C. 1970, ApJ, 160, 811

Kregel, M., van der Kruit, P. C., & de Grijs, R. 2002, MNRAS, 334, 646

Martin, C. L., & Kennicutt, R. C., Jr. 2001, ApJ, 555, 301

Pérez, I. 2004, A&A, 427, L17

Pohlen, M., Dettmar, R.-J., & Lütticke, R. 2000, A&A, 357, L1

Pohlen, M., Dettmar, R.-J., Lütticke, R., & Aronica, G. 2002, A&A, 392, 807

Pohlen, M., Beckman, J. E., Hüttemeister, S. H., Knapen, J. H., Erwin, P., & Dettmar, R.-J. 2004, In Penetrating Bars through Masks of Cosmic Dust: The Hubble Tuning Fork Strikes a New Note, ed. D. L. Block, I. Puerari, K. C. Freeman, R. Groess, & E. K. Block (Dordrecht: Springer), 713

Schaye, J. 2004, ApJ, 609, 667

Smith, J.A., Tucker, D.L., Kent, S.M., et al. 2002, AJ, 123, 2121

Trujillo, I., & Pohlen, M. 2005, ApJ, 630, L17

van der Kruit, P. C. 1979, A&AS, 38, 15

van der Kruit, P. C., Searle, L., 1981, A&A 95, 105