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The Good, the Bad, and the Ugly: Three Types of Disks

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Abstract. We briefly review the revised classification of the radial surface brightness profiles focusing on the outer disk structure, discussing possible formation scenarios, and posing some open questions.

1. Part I: The Early Days

The Setting and History

To study the fossil record of disk galaxy formation, one can either focus on the halo structure of nearby disk galaxies, e.g., in M 31 by Ibata et al. (2005) or NGC 4013 by Martínez-Delgado et al. (2008), or analyze the disk structure itself. Outer disks, now observable out to at least $z \sim 1$ (Pérez 2004; Trujillo & Pohlen 2005), contain valuable direct information about the buildup of disk galaxies and provide statistical samples on Gyr timescales.

We first summarize historically. We have the 'good' profiles, classified by Freeman (1970) as Type I, where the radial light distribution is a simple, exponential decline out to at least 5 scale lengths, often showing a sharp cut-off (van der Kruit 1979). Nevertheless, from the beginning some profiles were 'bad' (or at least 'less good'), e.g., the Type II profiles of Freeman (1970), and others not well described by a simple exponential (e.g. seen in the compilation by radial profiles of Courteau 1996). Also de Grijs et al. (2001) and Pohlen (2001) showed that the sharp cut-offs seen by van der Kruit (1979) are not complete, but better described with broken exponentials as seen in face-on galaxies (Pohlen et al. 2002).

2. Part II: The Current Story

The Data and Score

To avoid problems due to line-of-sight integration for edge-on systems (see e.g. Pohlen et al. 2004) and assuming that edge-on and face-on galaxies have the same radial structure, we gathered a large data set of intermediate to face-on disk galaxies. The data are split into two subsets: an early-type (S0-Sb), diameter and distance limited sample of 108 galaxies and a late-type (Sb-Sm), volume limited sample ($D \lesssim 46\,\mathrm{Mpc}$, $M_{\mathrm{abs}} < -18.4\,\mathrm{B\text{-}mag}$) of 85 galaxies. For details see Erwin et al. (2005, 2008), Gutiérrez et al. (in preparation), Erwin et al. (in preparation), and Pohlen & Trujillo (2006).

Using these data we present a revised classification scheme for radial profiles of disk galaxies. We find some Freeman Type I profiles, with single exponentials down to the noise level. Pohlen & Trujillo (2006) show in their late-type sample, that these are unchanged out to $6-8$ scale lengths in many cases and most probably have no hidden truncations below the noise (see Pohlen & Trujillo 2006, for more details). We also extended Freeman's original Type II[1] class to include now the 'downbending' exponential breaks in the outer disk (van der Kruit's original truncations). Finally, Erwin et al. (2005) defined a third, top level class of profiles, called Type III (the 'ugly'), having broken exponentials but with an 'upbending' profile, i.e., shallower beyond the break (Fig. 1).

The Sanity Check and Origin

There is an active debate (van der Kruit, this volume, and Florido et al. (2006) vs. Pohlen et al. (2007)) on whether what is seen in edge-on galaxies is the same phenomenon as that now well described for many intermediate to face-on galaxies. Fortunately there is an independent consistency check using an entirely different method. With star counts for nearby galaxies, the radial profile can be traced out to very large radii ($\mu > 30$ mag arcsec^{-2}). Local counterparts for each of our top level classes are found: NGC 300 (Type I, Bland-Hawthorn et al. 2005), M 33 (Type II, Ferguson et al. 2007), M 31 (Type III, Ibata et al. 2005).

We now look at the theoretical underpinning of this classification. Type II profiles are quite a mixed bag of systems (only grouped morphologically) for which there is a range of plausible explanations. The breaks near the centers of barred galaxies are probably bar related (see Erwin et al. 2008, for more details), and the breaks further out, are probably due to star formation thresholds (Kennicutt 1989; Schaye 2004; Elmegreen & Hunter 2006; Li et al. 2006) or to (bar) resonances (Debattista et al. 2006; Erwin et al. 2008). Roškar et al. (this volume) present simulations combining both effects. Type III, being recent, has not received so much attention. In some cases Type III profiles are observed in interacting systems, and Younger et al. (2007) produce upbending profiles in models with minor mergers. However, Elmegreen & Hunter (2006) can also produce these breaks by tweaking the gas density in disk star formation models. Type I profiles, though the simplest and the longest known, are the least understood, with viscous evolution (Lin & Pringle 1987) being the main candidate mechanism.

From this we can now re-characterize the disk-profile types. Type II profiles are 'the good', with fairly convincing theoretical models, Type III's are 'the not so bad', while Type I's, the least understood, are 'the ugly'. For example, if

[1]Note: Our top level classification (I-III) is purely morphological and so the Type II galaxies are a 'mixed bag' that certainly formed in a variety of ways. This is reflected in our more refined sub-classification scheme –left out for clarity here– which is described in detail in the papers mentioned above.

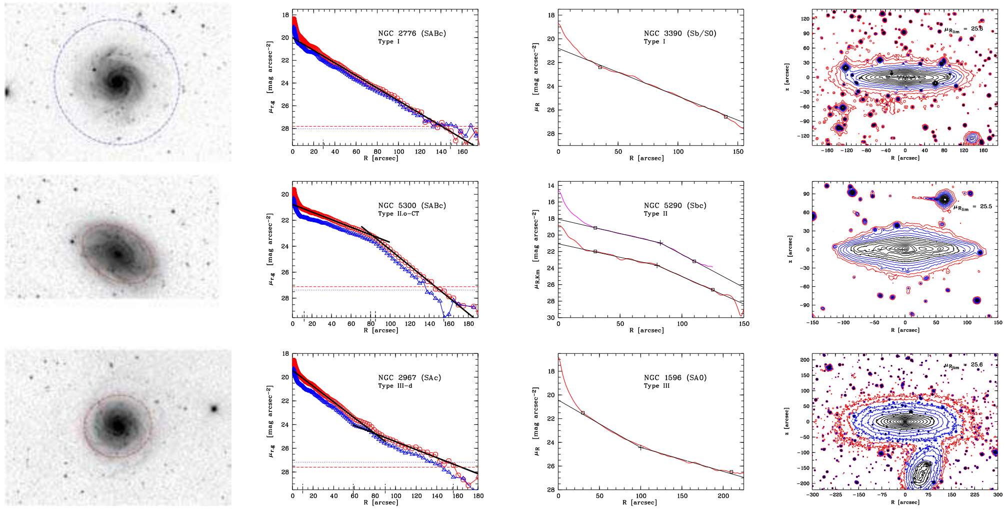

Figure 1. Prototypical examples for each class of profiles, Type I, Type II, and Type III (top to bottom) for face-on (left columns) and edge-on (right columns) galaxies (Pohlen & Trujillo 2006; Pohlen et al. 2007).

there is a general star formation threshold we would not expect to see a single Type I profile. This is in no way a 'happy ending' so in Part III we present some of the open theoretical and observational questions still to be resolved.

3. Part III: The Last Act

Further Observational Evidence

If we combine early- and late-type galaxy samples we find as yet unexplained correlations between Hubble type and disk-profile type. The frequencies of Type I and Type III increase to earlier Hubble type, while the Type II frequency falls (see Erwin et al., this volume, including further correlations, comparing e.g., barred vs. unbarred or field vs. cluster). The vertical structure (returning to edge-on galaxies) gives more constraints to help decide the origin of the disk-profile types. Pohlen et al. (2007) showed that our profile classification does not depend on observational geometry, by deprojecting a pilot sample of edge-on galaxies and producing face-on-equivalent radial profiles (see Fig. 1). But from the dependence of the deprojected profiles on height above the plane beyond the break radius they also find an enhanced profile flattening. Could this 'weakening of the truncation' be an age effect? Perhaps the mechanism causing the break acts on the young stars forming close to the plane, but is diluted with height due to the enhanced velocity dispersion of the older stars? Although this would be consistent with a star formation threshold, de Jong et al. (2007) have recently shown that for NGC 4244 the broken exponential shape is similar for old and young stars, which argues against this simple scenario.

Outlook

Despite the above theoretical and observational advances, there are many remaining open questions. How good are our observational indicators for star formation (thresholds)? From Gil de Paz et al. (2005) the UV profile seems to follow the underlying stellar distribution, showing (for example) a Type III behavior. Christlein et al. (this volume) presents profiles in which the Hα shows the same downbending broken exponential as the continuum, albeit slightly steeper. So, is the underlying stellar disk really driven by star formation or vice versa? Is the break a purely dynamical effect? Is the 'weakening of truncation' an observation of the often quoted 'flaring' in the outer disk? There may in fact be a connection between truncations and warps (van der Kruit, this volume), but we lack a detailed radial comparison of gas distribution with the underlying stellar disk for the different disk-profile types.

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