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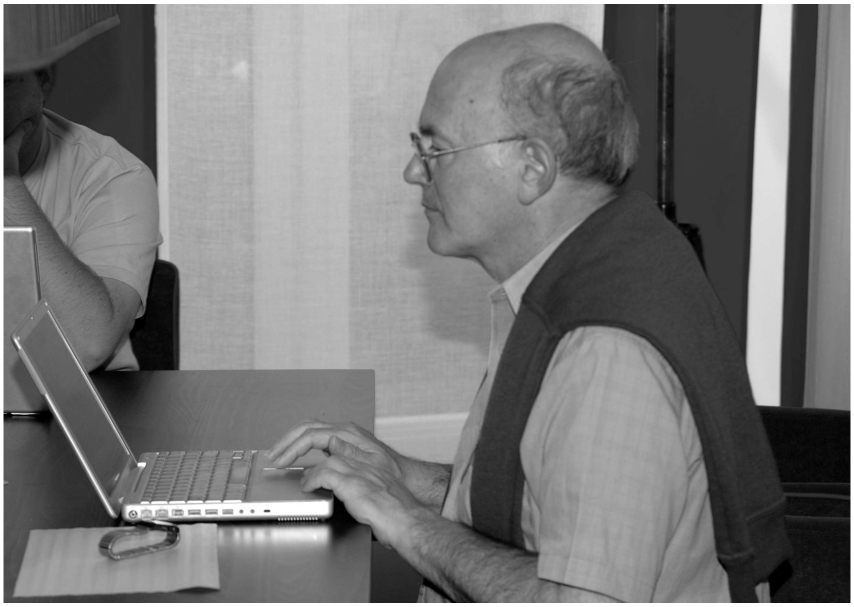
PROPERTIES OF STELLAR DISKS



Ken Freeman at work.

STELLAR DISKS

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Abstract I review the properties of galactic stellar disks. The review includes the famous van der Kruit & Searle papers of the early 1980s, recent work on the structure of the outer regions of galactic disks including the problem of the radial truncation of disks, and galactic thick disks.

Keywords: galaxies: spiral - galaxies: structure - galaxies: halo - galaxies: abundances

1. Introduction

The disk is the defining stellar component of disk galaxies. It is the end product of the dissipation of most of the baryons, and contains almost all of the baryonic angular momentum. Understanding its formation is probably the most important goal of galaxy formation theory.

Out of the chaotic hierarchical disk formation process come galactic disks with a high level of regularity in their structure and scaling laws. We need to understand the reasons for this regularity. In a series of four papers, following on from van der Kruit (1979), van der Kruit & Searle (1981a,b; 1982a,b) used surface photometry of a sample of edge-on spirals to establish most of the basic properties of disk galaxies, and laid the foundations of today's studies of galactic disks.

2. The van der Kruit & Searle papers

Van der Kruit & Searle (vdKS) established:

- the underlying structure of galactic disks. The luminosity density distribution $L(R, z)$ is roughly exponential in radius R and height z, following a distribution of the form

  $$L(R, z) = L_\circ \exp(-R/h_R)\mathrm{sech}^2(\mathrm{z}/\mathrm{z}_\circ)$$

  or

  $$L(R, z) = L_\circ \exp(-R/h_R) \exp(-z/h_z)$$

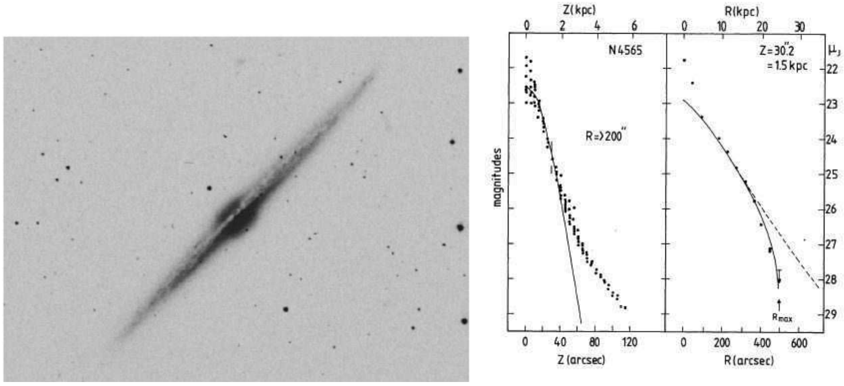

Figure 1. The galaxy NGC 4565 (left panel) and its surface brightness profiles in z and R, from van der Kruit & Searle (1981a). The $z-$profile shows the dominance of the thick disk above a height $z = 50$ arcsec. The $R-$profile shows the onset of radial truncation at a radius $R = 300$ arcsec.

with the vertical scaleheight h_z or $z_\circ$ approximately independent of radius.

- that this form of the luminosity distribution $L(R, z)$ holds out to $R = 3$ to 5 radial scale lengths, after which it is often truncated.
- the prevalence of thick disks which envelop the $L(R, z)$ light distribution of the thin disks.

Figure 1 shows one of the edge-on galaxies (NGC 4565) investigated by vdKS. This system has a small bulge and a prominent thick disk. The disk properties which vdKS established are clearly visible in their surface photometry for this galaxy.

From Jeans' equations, and assuming constant M/L ratio throughout the disk, the approximately double exponential structure with its constant scaleheight implies that the stellar velocity dispersion components in the disk should change with radius as $\sigma \sim \exp(-R/2h_R)$. This exponential decline in velocity dispersion is observed in the Milky Way and other spirals. Figure 2 shows the radial change in velocity dispersion observed by van der Kruit & Freeman (1986) for the disk of the spiral NGC 5247, and by Lewis & Freeman (1989) for the disk of the Milky Way.

Simulations of disk formation show a complex interplay of gravitational and hydro-dynamical effects. The details are not well understood, and the reason for the exponential form of the radial light distribution is not yet clear. Extreme options include

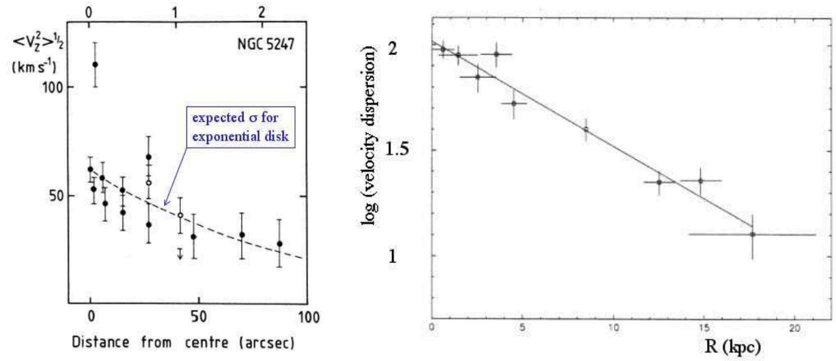

Figure 2. *Left:* The radial decrease of the z-component of the velocity dispersion in the spiral NGC 5247 (from van der Kruit & Freeman 1986). *Right:* The radial decrease of the R-component of the velocity dispersion for the thin disk of the Milky Way (from Lewis & Freeman 1989). The disk of the Milky Way is approximately exponential in R and z, with scaleheight of about 300 pc and scalelength of about 3.5 kpc. The velocity dispersion decreases from about 100 km/s near the center (similar to the velocity dispersion of the bulge) to about 15 km/s at a radius of 18 kpc.

- the collapse of a torqued gas cloud with the appropriate internal angular momentum distribution $M(j)$ within a dark halo, conserving its $M(j)$ to give an exponential gas disk in place before star formation began (e.g., Fall & Efstathiou 1980).
- the gas in the disk is radially redistributed by viscous torques: this process tends to an exponential disk if the star formation timescale $\sim$ viscous timescale (e.g., Lin & Pringle 1987).

The vertical structure of disks (Fig. 3) is directly associated with their star formation history and dynamical history. Spiral arm heating, scattering by giant molecular clouds, accretion and warping can all contribute to heating the disk vertically and generating a a vertical scale height h_z for the old thin disk that is usually about 200 to 300 pc.

3. The Outer Regions of Disks

First we discuss the radial truncation of galactic disks. The truncation is more easily seen in in edge-on galaxies than in face-on galaxies. Figure 4 shows two images of the edge-on spiral NGC 4565, printed with different stretches. In the deep stretch, one can see that the disk appears thicker in z, but its radial extent has hardly changed. Figure 5 shows the correlation between the truncation radius $R_{\max}$ and the radial scalelength for a sample of edge-on disks.

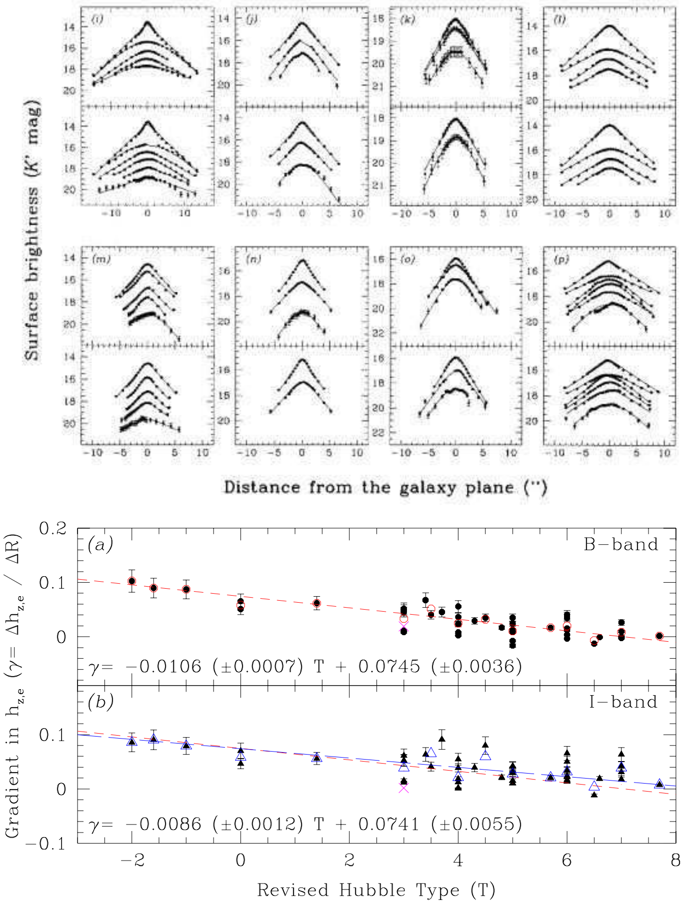

Figure 3. *Top:* Vertical brightness profiles in a sample of edge-on disk galaxies. Each panel shows the approximately exponential surface brightness distribution for one galaxy, at a range of radial distances from their centers (de Grijs et al. 1997). *Bottom:* The radial variation of the scaleheight as a function of Hubble type, for a sample of edge-on galaxies from de Grijs & Peletier (1997). The earlier-type galaxies show a gradient in the scaleheight, with h_z increasing with radius. For the spirals later than T = 5 (Sc), the gradient in scaleheight is small.

The surface brightness profile of the Local Group spiral M33 has recently been measured to very faint levels (about 31 mag arcsec^{-2}) by Ferguson et al. (2006), using surface photometry and star counts. This galaxy shows a classical exponential disk extending to a truncation radius of about 5 radial scale lengths, beyond which the surface brightness profile breaks to a steeper exponential with a much shorter scale length. This double exponential radial structure is a common form of radial truncation. Ferguson et al. were able to

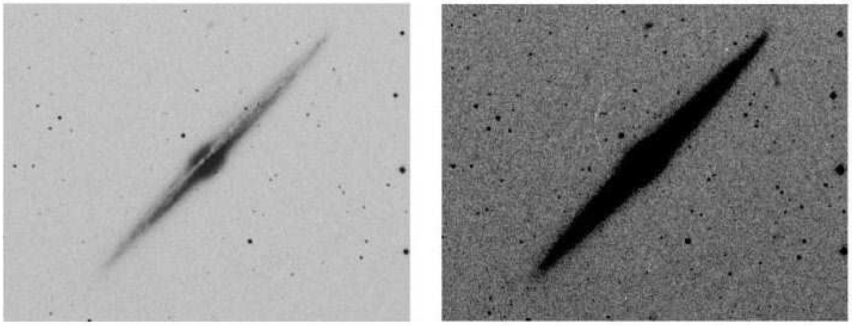

Figure 4. The edge-on spiral NGC 4565. The image (from the DSS) is shown at two different stretches to illustrate the radial truncation of the thin disk.

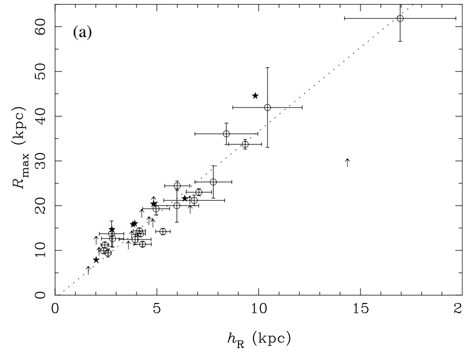

Figure 5. For a sample of 34 edge-on disk galaxies, Kregel et al. (2002) find $R_{\rm max}/h_R = 3.6 \pm 0.6$.

trace the stellar disk of M33 out to a radius of about 1 degree; the HI distribution extends even further (Corbelli et al. 1989).

What is the origin of the radial truncation of galactic disks? Here are a few of the many possibilities which have been discussed.

- the truncation radius is associated with the maximum angular momentum of the disk baryons in the proto-galaxy. This now seems unlikely because many disks have HI extending well beyond the truncation radius.

- star formation is believed to be regulated by disk instability (Kennicutt 1989), and the truncation radius is where the gas density goes below the critical value for star formation. This seems a likely explanation.

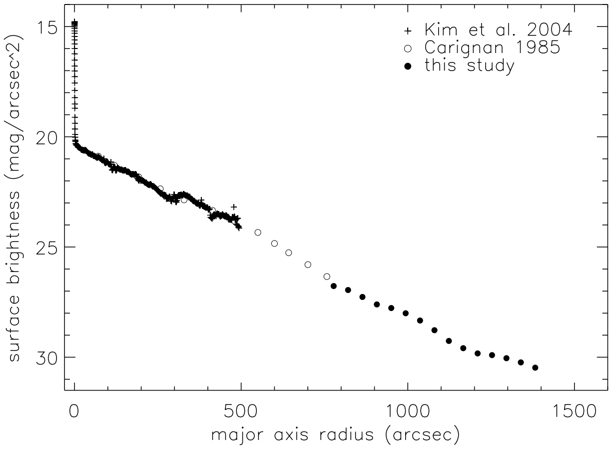

Figure 6. The surface brightness profile of NGC 300 shows no truncation out to a radius of about 10 scale lengths (Bland-Hawthorn et al. 2005).

- disks continue to grow by accretion up to the present time, and the truncation radius is the radius to which the disk has grown today. This seems unlikely: although the outer disks of spirals do appear to be younger than the inner disks, they are still typically many Gyr old (e.g., Bell & de Jong 2000). In some galaxies, like M83 and the Milky Way, star formation continues in the outer disk but there is an underlying old component. The color-magnitude diagram of the stars in the outer disk of M33 (Ferguson et al, in preparation) shows an intermediate/old, fairly metal-poor ([Fe/H] ~ -1.2) stellar population dominating the outer disk of M33.

Although radial truncation of disks is common, it is not ubiquitous. Bland-Hawthorn et al. (2005) have measured the structure of the late-type Sculptor group spiral NGC 300, which is rather similar to M33 but about 3 times more distant. Combining surface photometry from other sources with deep star counts from images with the Gemini GMOS, complete to magnitude $r' = 27$, the disk of NGC 300 appears to be exponential for at least 10 scale lengths without truncation (see Figure 6). As for M33, the HI distribution extends beyond the maximum radius reached by the star counts.

Pohlen & Trujillo (2006) propose three classes of structure in the outer regions of disks. Type I is like NGC 300, showing a single untruncated exponential disk out to the limit of the photometry. Type II is like M33, with an inner exponential disk breaking to a steeper exponential disk in the outer regions. In the type III systems, there are again two exponential components, but the outer component has a *longer* scalelength than the inner component.

The structure and truncation of outer disks is not understood yet: it remains an interesting problem.

Recent HI observations by Koribalski et al. (unpublished) of the nearby giant spiral M83 shows a complex filamentary structure in its outer disk, extending to a radius of about 100 kpc. Some of these filaments coincide with the faint outer optical structures observed earlier by Malin & Hadley (1997); others do not. Some of the outer HI filaments are sites of star formation observed with GALEX (Thilker et al. 2005). The HI structure has the appearance of tidal filaments, possibly HI extracted from the inner disk of M83 by tidal interaction with a nearby dwarf galaxy. The presence of star formation in these filaments may be demonstrating a way of building an outer stellar disk through tidal interactions of the inner disk. The very extended star formation in the outer disk of M83 is particularly interesting in the context of new results on the outer disk of M31 and the Milky Way.

4. The Outer Regions of M31 and the Galaxy

HST photometry of stars in the outermost regions of M31 give an estimate of the stellar metallicity distribution (e.g., Worthey et al. 2005). Figure 7 shows how the abundance gradient in M31 continues out to a radius of about 15 kpc, but thereafter the mean stellar metallicity remains constant with radius at about $[Z/H] = -0.5$ out to a distance of 50 kpc. Irwin et al. (2005) show that the surface brightness distribution along the minor axis shows the usual $r^{\frac{1}{4}}$ distribution out to about 15 kpc, but thereafter is approximately exponential to a radius of about 50 kpc, indicating the presence of an extended outer exponential disk. Guhathakurta et al. (this conference) argue that the halo of M31 extends even further, out to a radius of about 150 kpc.

New kinematical data confirms that the disk of M31 extends beyond 50 kpc (10 scalelengths). The outer disk is rotating almost as rapidly as the inner disk (Ibata et al. 2005), with a small rotational lag and a velocity dispersion of about 30 km s^{-1}. Stars in fields out to 80 kpc, away from the M31 stellar stream, have typical lags of 54 km s^{-1} and dispersions of 37 km s^{-1}. Ibata et al. argue that the outer disk formed from accretion of many small subgalactic structures. Its disk-like stellar kinematics indicate that the accreted matter probably came into M31 in mainly gaseous form, rather in already formed stars. The color-magnitude diagrams in the outer disk of M31 suggests that the stars of the outer disk are fairly old (several Gyr), as in M33 and the Galaxy. The red giant branch colors indicates a (47 Tuc)-like stellar population in outer disk, similar over wide range in radius, and consistent with the observed constant chemical abundance in the outer disk.

The abundance distribution in the outer disk of the Milky Way appears remarkably similar to that of M31. Yong et al. (2005) and Carney et al. (2005)

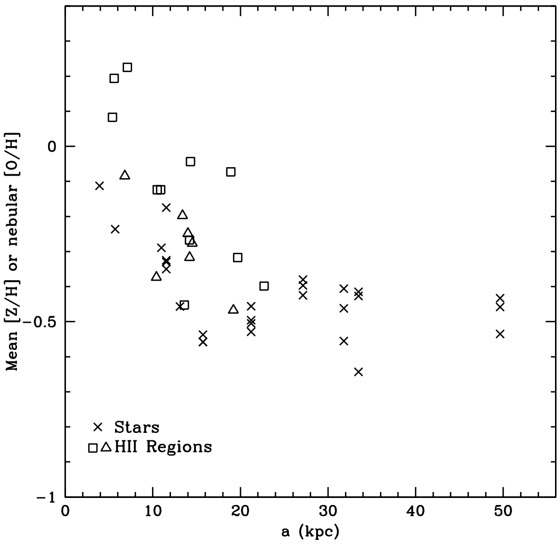

Figure 7. The metallicity gradient in the disk of M31 (Worthey et al. (2005). The gradient bottoms out at a radius of about 15 kpc and an abundance of [Z/H]~ -0.5.

measured the chemical properties of open clusters and stars in the outer disk. The radial abundance gradient for the open clusters (ages 1 to 5 Gyr) in the galactic disk bottoms out, at a radial R_G = 10 to 12 kpc (R_G = 15 kpc in M31), and at an abundance of [Fe/H] = -0.5 (as in M31). The outer disk is α-enhanced, with [α/Fe] = + 0.2, and is also Eu-enhanced, indicating a fairly rapid history of star formation and chemical evolution in the outer disk. Yong et al. argue that the outer disk stars formed from reservoir of gas that had a different star formation history from the solar neighborhood (for which the star formation rate has been roughly constant over the last 10 Gyr: e.g. Rocha-Pinto et al. 2000). Star formation in the outer disk may have been triggered by a merger event.

Carney et al. (2005) also measured abundances in Cepheids of the outer disk, which are significantly younger than their 1-5 Gyr-old open clusters. The Cepheids show a weaker abundance gradient than the clusters, and they are also less alpha-enhanced: see Figure 8. The abundance gradient in the galactic disk has flattened with time, as the associated duration of chemical evolution has lengthened, from the open clusters to the Cepheids, with abundances tending towards the solar values.

To summarize this section on outer disks:

- tidal effects as in M83 may contributed to building up the very extended disks of some spirals. Gas tidal stripped from the inner galaxy builds up

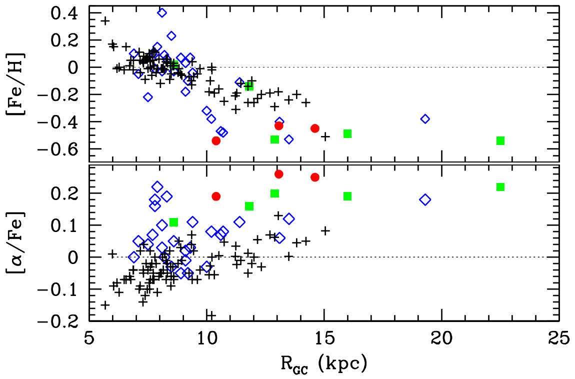

Figure 8. The radial abundance gradient in the outer disk of the Milky Way (from Carney et al. 2005). The + symbols show Cepheids, and the other symbols are open clusters in the Galaxy. The Cepheids are younger than the open clusters. The abundance gradient in the disk has flattened with time, tending towards solar values.

the outer disk. In M83, a low level of star formation is observed in the outer gas.

- the disks of some spirals, like M31 and NGC 300, extend out beyond 10 radial scale lengths.
- the outer disks of M31, M33 and the Milky Way include a stellar population that is at least several Gyr old.
- the radial abundance profiles in the outer disks of M31 and the Galaxy are approximately constant at [Fe/H] ~ -0.5 beyond a radius of about 15 kpc. The older stars of the outer galactic disk show α-enhancement, indicating a relatively short duration of chemical evolution.

5. Thick Disks

Most spirals have a second disk component, the thick disk, enveloping the thin disk. Figure 9 shows the thick disk of the edge-on S0 galaxy NGC 4762. This galaxy has an unusually prominent thick disk that is readily visible in images. Our Galaxy has a thick disk with a mass about 10% of the mass of the thin disk. It is old ($>$ 12 Gyr) and significantly more metal poor than the thin disk: its mean [Fe/H] ~ -0.7 and it is α-enhanced, as seen in Figure 10. It is rapidly rotating, lagging the rotation of the thin disk by only about 50 km s^{-1}: see Freeman & Bland-Hawthorn (2002) for references.

Figure 11 shows a 2MASS image of the edge-on spiral NGC 5907. Only the thin disk is visible, but surface photometry shows a prominent thick disk appearing at a surface brightness of $\sim$ 25 R mag arcsec $^{-2}$.

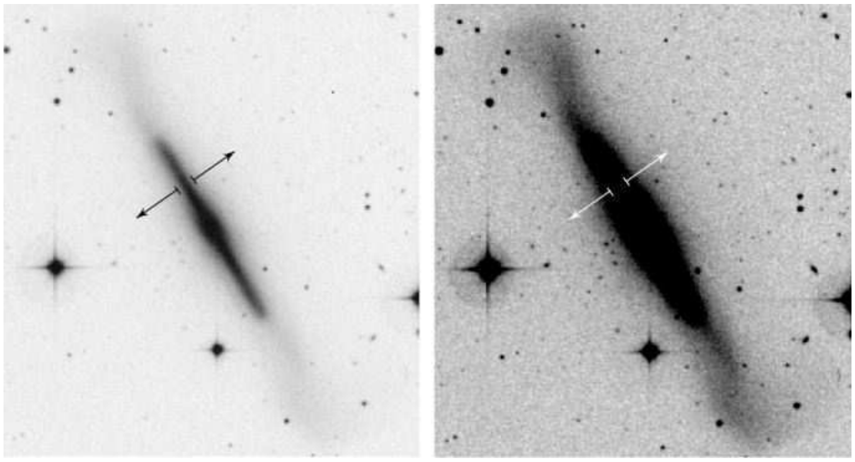

Figure 9. The edge-on S0 galaxy NGC 4762. The blunt ends of the arrow show the approximate extent of the thin disk. The thick disk can be seen in the deeper stretch extending vertically well beyond the thin disk.

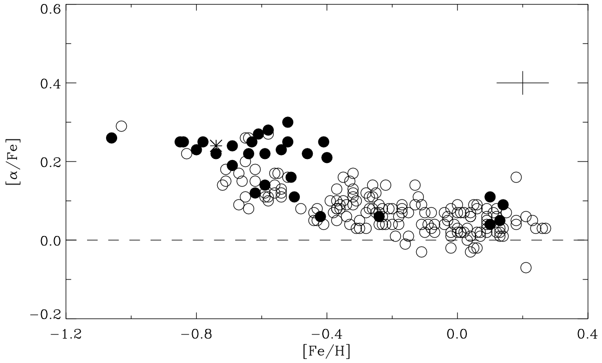

Figure 10. [α/Fe] vs. [Fe/H] for stars of the galactic thin (open circles) and thick (filled circles) disks (selected kinematically), showing the $\alpha-$ enhancement of most of the thick disk stars. Higher [α/Fe] is associated with more rapid star formation. From Nissen (2004).

Dalcanton & Bernstein (2002) made BRK surface photometry of 47 late-type edge-on disk galaxies. They find that all are embedded in a flattened low surface brightness red envelope or thick disk. From their colors, they estimate that the typical ages of these red envelopes are > 6 Gyr and that they are not very metal poor, so they appear similar to the thick disk of the Milky Way. They argue that the formation of a thick disk is a nearly universal feature of formation of disk galaxies.

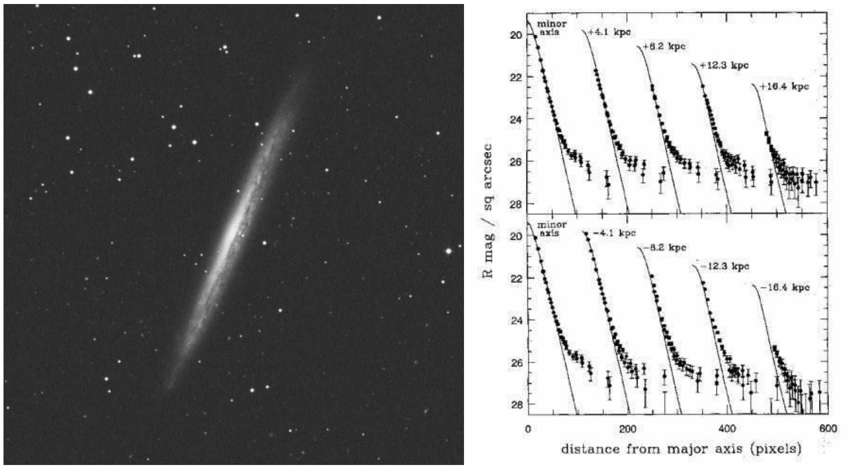

Figure 11. *Left:* Image of the edge-on galaxy NGC 5907. *Right:* Vertical surface brightness profiles at different radii: the curve shows the surface brightness distribution of the thin disk. The thick disk appears in all of the vertical cuts at a surface brightness of about 25 R mag arcsec^{-2} (from Morrison et al. 1994).

To summarize the current view of thick disks: thick disks are almost ubiquitous and appear to form early ($>$ 6 Gyr ago, 12 Gyr ago in the Galaxy) and rapidly, through the heating of the early thin disk in an epoch of merging (e.g., Quinn & Goodman 1986) or from early accretion of satellites, probably in mainly gaseous form (e.g., Brook et al. 2004). Thick disks appear to be dynamically and chemically distinct from the thin disks of their parent galaxies.

Yoachim & Dalcanton (2005) have made an interesting first measurement of the rotation of the thick disks in two edge-on spirals. This is a difficult observation, because it is necessary to separate the contributions of the thin and thick disks to the spectra of the faint regions away from the equatorial plane, using the surface photometry of the individual galaxies. For one of their galaxies (FGC 227), their data indicate that the thick disk may be counter-rotating relative to the thin disk. If this turns out to be correct, then it would exclude heating of an early thin disk as the origin for the thick disk in this galaxy.

At least one edge-on disk galaxy, NGC 4244 (Fry et al. 1999) appears to be a pure thin disk. Surface brightness cuts perpendicular to its disk show only a single exponential component, with no indication of a thick disk component down to a surface brightness level of about $\mu(R) = 28$ mag acrsec^{-2}. See Fig. 12.

The existence of such a pure disk galaxy is interesting because, at least for some late-type disks

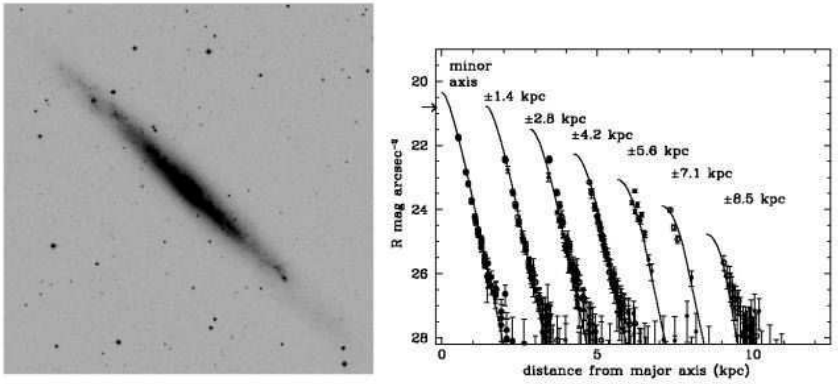

Figure 12. *Left:* Image of the edge-on galaxy NGC 4244. *Right:* Vertical surface brightness profiles at different radii: the curve shows the surface brightness distribution of the thin disk. From Fry et al. (1999).

- the star formation did not start before the gas had settled to the disk plane
- since the onset of star formation in the disk, the the disk has suffered no significant dynamical disturbance from internal or external sources

We note that pure disk galaxies like NGC 4244 are not readily produced in ΛCDM simulations, because there is too much merger activity.

How did pure disk galaxies avoid any significant star formation until the baryons had settled to thin disk? We might expect that the aggregation process with its interacting lumps of dark matter and baryons should lead to star formation as it does in present-day interacting systems. The baryons need to be maintained in a state such that they can settle quiescently to the disk, for example via winds or baryon blowout driven by early star formation and supernovae (e.g., Sommer-Larsen et al. 1999).

6. Summary

- disks typically have the exponential structure in R and z: some are truncated radially at a few scalelengths
- the radial exponential structure and radial truncation of galactic disks are still not well understood
- thick disks are very common but not 100% ubiquitous
- the existence of pure (thin) disk galaxies means that at least some disks form in a very quiescent manner, with no star formation until the disk had settled, and with an undisturbed history thereafter.

7. Conclusion

Best wishes to Piet van der Kruit on his appointment to the Jacobus Kapteyn chair. I express my appreciation for the illumination which he and his students have brought to the subject of disk galaxies, and my gratitude for a long and continuing collaboration.

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