STRUCTURE, MASS AND STABILITY OF GALACTIC DISKS

Piet van der Kruit
Kapteyn Astronomical Institute
University of Groningen
the Netherlands

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Stellar disks

- Ken Freeman *is an expert in many area's of astronomy, but he is in particular known for his research in that of disks of spiral galaxies.*
- *I feel fortunate to have been able to work with him on projects related to that.*
- *Many congratulations, Ken, and thanks for all the years of friendship and stimulating collaboration.*

I will review the measurements on the stellar velocity dispersions in galaxy disks and address matters concerning disk masses and the related issues mass-to-light ratios, local stability and the maximum disk hypothesis.
I will end with a few words on truncations.

- Radial distribution of surface brightness is an exponential[1]
- Vertical distribution approximately an isothermal sheet[2] with a scaleheight that is independent of radius.
- A more general form is[3]

$$L(R,z) = L(0,0)\,\mathrm{e}^{-R/h}\,\mathrm{sech}^{2/n}\left(\frac{nz}{2h_{\mathrm{z}}}\right),$$

ranging from the isothermal ($n = 1$) to the exponential ($n = \infty$) and allows for more realistic stellar distributions in z.
- From actual fits[4] in I and K'

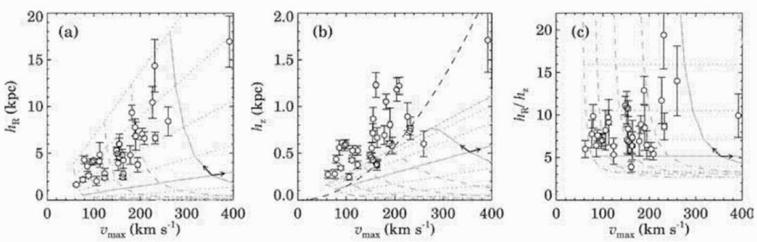
$$2/n = 0.54 \pm 0.20.$$

[1]K.C. Freeman, Ap.J. 160, 811 (1970)
[2]P.C. van der Kruit & L. Searle, A&A 95, 105 (1981)
[3]P.C. van der Kruit, P.C., A&A 192, 117 (1988)
[4]R. de Grijs, R.F. Peletier & P.C. van der Kruit, A&A 327, 966 (1997)

- There are important correlations between various properties.
- Very useful ones are those between V_{rot} and scaleparameters h and h_{z}[5], such as

$$h_{\mathrm{z}} = (0.45 \pm 0.05)\,(V_{\mathrm{rot}}/100\ \mathrm{km\ s^{-1}}) - (0.14 \pm 0.07)\ \mathrm{kpc}$$

with an r.m.s. scatter of 0.21 kpc.



[5] M. Kregel, P.C. van der Kruit & K.C. Freeman, MNRAS 358, 503 (2005)

Vertical stellar dynamics

The Poisson equation for the case of axial symmetry and at low z reads[6]

$$\frac{\partial K_{\rm R}}{\partial R} + \frac{K_{\rm R}}{R} + \frac{\partial K_{\rm z}}{\partial z} \approx 2(A-B)(A+B) + \frac{\partial K_{\rm z}}{\partial z} = -4\pi G\rho(R,z)$$

For a flat rotation curve $A = -B$ and $2(A-B)(A+B) = 0$, so the plane-parallel case becomes an excellent approximation[7].
The equation of hydrostatic equilibrium when the disk is exponential in both the radial and vertical direction:

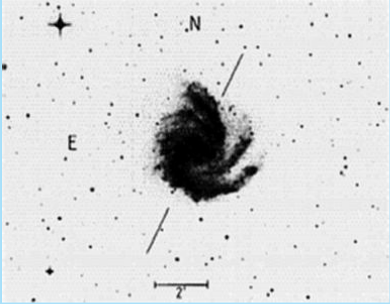
$$\sigma_{\rm z}(R,z) = \sqrt{\pi G h_{\rm z}(2-e^{-z/h_{\rm z}})(M/L)\mu_0}\; e^{-R/2h},$$

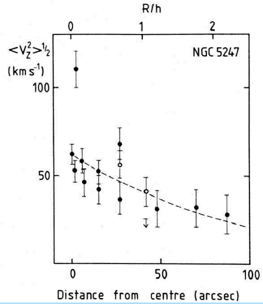
For a constant M/L the disk thickness increases with twice the photometric scalelength.

[6] J.H. Oort, Stars & Stellar Systems 5, ch.21 (1965)
[7] P.C. van der Kruit & K.C. Freeman, K.C., Ap.J. 303, 556 (1986)

Ken and I[8] were the first to confirm that in NGC 5247:

$$\langle V_z^2 \rangle^{1/2} = (62 \pm 7)\,\mathrm{exp}\,[-(0.42 \pm 0.10)\ R/h]\ \ \mathrm{km\ s^{-1}}$$



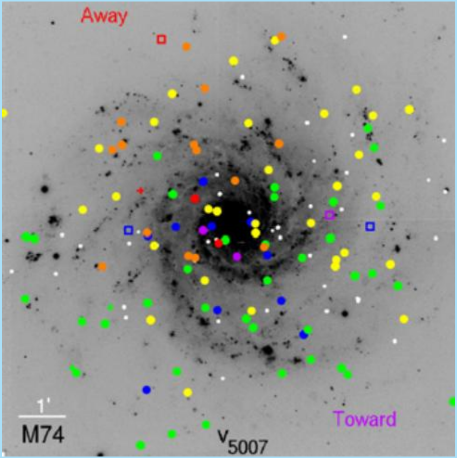


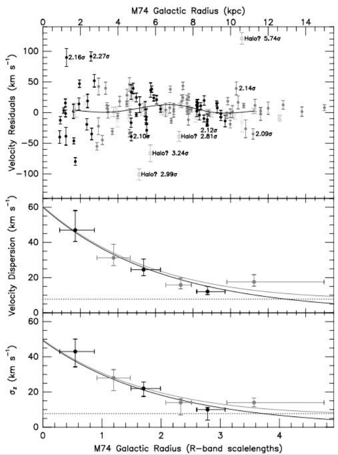
[8] P.C. van der Kruit & K.C. Freeman, K.C., Ap.J. 303, 556 (1986)

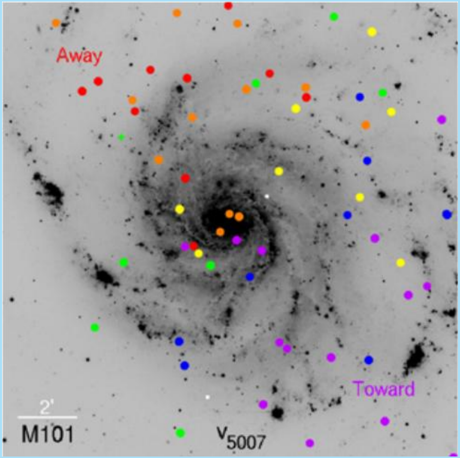
- So M/L appears constant with radius.
- This has been confirmed in later studies[9], but recently in much detail in two important new studies.
- The first is the use of planetary nebulae as test particles in disks of five face-on spirals[10].
- This method allows measurement of the velocity dispersion of the old disk population to be measured out to large radii.
- The findings are that except for one system (M101), the M/L is constant out to about three radial scalelengths. Outside that radius the velocity dispersion seems to stop declining and becomes flat with radius.

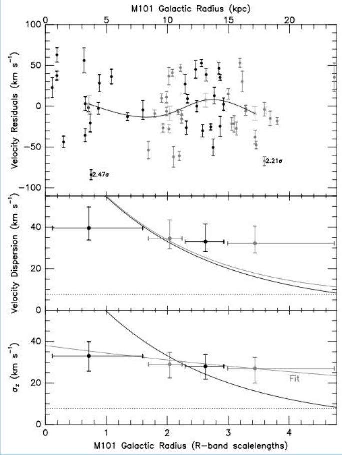
[9] E.g. R. Bottema, A&A 275, 16 (1993); M. Kregel, P.C. van der Kruit & K.C. Freeman, MNRAS 358, 503 (2005); and referecnes therein

[10] K.A. Herrmann & R. Ciardullo, Ap.J. 705, 1686 (2009)


Away
Toward
1'
M74
V5007


M74 Galactic Radius (kpc)
Velocity Residuals (km s^{-1})
Velocity Dispersion (km s^{-1})
σ_z (km s^{-1})
M74 Galactic Radius (R–band scalelengths)


Away
Toward
2'
M101
V5007


M101 Galactic Radius (kpc)
Velocity Residuals (km s⁻¹)
2.47σ
2.21σ
Velocity Dispersion (km s⁻¹)
σz (km s⁻¹)
Fit
M101 Galactic Radius (R−band scalelengths)

- The second development is the Disk Mass Survey of Marc Verheijen, Matt Bershady, Kyle Westfall and Rob Swaters and co-workers.
- In this study they exploit the power of integral field units.
- They summarize their findings by the statement

  "Kinematics follows light"

- Again the evidence is that M/L is constant with radius.

Both studies find relatively low values for M/L and conclude that their galaxies are in general sub-maximal.

Picture deleted

"Courtesy of the Disk Mass Survey Team (priv. comm.)"

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"Courtesy of the Disk Mass Survey Team (priv. comm.)"

Stellar dynamics in the plane

- The radial and tangential stellar velocity dispersions are more complicated to determine.
- They are not independent, but governed by the local Oort constants:

$$\sigma_\theta/\sigma_{\rm R} = \sqrt{-B/(A-B)}.$$

- This results from the axis ratio of the epicyclic motion that describes stellar orbits deviating little from circular.
- The frequency in the epicycle is $\kappa = 2\sqrt{-B(A-B)}$ and its axis ratio $\sqrt{-B/(A-B)}$.[11]
- For a flat rotation curve $A = -B$, so $\sigma_\theta/\sigma_{\rm R} = 0.71$ and $\kappa = \sqrt{2}V_{\rm rot}/R$.

[11] J.H. Oort, Stars & Stellar Systems 5, ch.21 (1965)

- We can also use the asymmetric drift equation

$$V_{\rm rot}^2 - V_{\rm t}^2 = \sigma_{\rm R}^2 \left\{ \frac{R}{h} - R\frac{\partial}{\partial R}\ln(\sigma_{\rm R}) - \left[1 - \frac{B}{B-A}\right]\right\},$$

where the circular velocity $V_{\rm rot}$ can be measured with sufficient accuracy from the gas.

- The radial dispersion plays an important role in the Toomre Q-criterion[12] for local stability in galactic disks

$$Q = \frac{\sigma_{\rm R}\kappa}{3.36 G\Sigma}$$

with Σ the local mass surface density.

- In this criterion the disk is stabilized by random motions on small scales and by differential rotation on large scales.
- Numerical simulations suggest that galaxy disks have $Q =$ 1.5–2.5 and are on the verge of instability.

[12] A. Toomre, Ap.J. 139, 1217 (1964)

- There are two possible assumptions for the radial dependence of the velocity dispersions[13]:
  - The axis of the velocity ellipsoid $\sigma_\theta/\sigma_{\rm R}$ is constant, or
  - the Toomre parameter Q is constant with radius.
- Out to a few scalelengths this is not much different.
- A detailed study in edge-on systems[14] has been made in a sample of 15 galaxies[15] using the first assumption.
- This leads to a value of the mass-to-light ratio M/L up to a factor depending on the axis ratio of the velocity ellipsoid.

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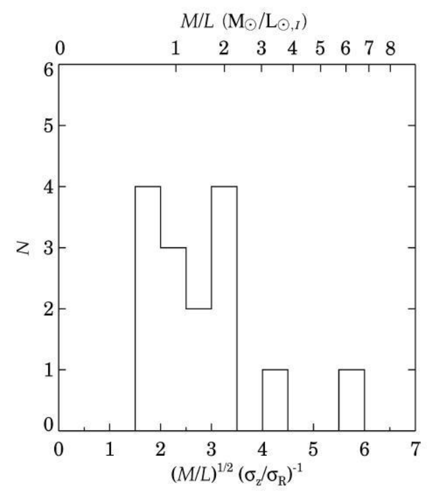
[13] P.C. van der Kruit & K.C. Freeman, Ap.J. 303, 556 (1986)

[14] Using photometry from M. Kregel, P.C. van der Kruit & R. de Grijs, MNRAS 334, 646 (2002)

[15] M. Kregel, P.C. van der Kruit & K.C. Freeman, MNRAS 358, 503 (2005)

- If $\sigma_\theta/\sigma_\mathrm{R}$ is of order 0.6 (top scale) we see that most galaxies have $M/L \sim 1$–2.



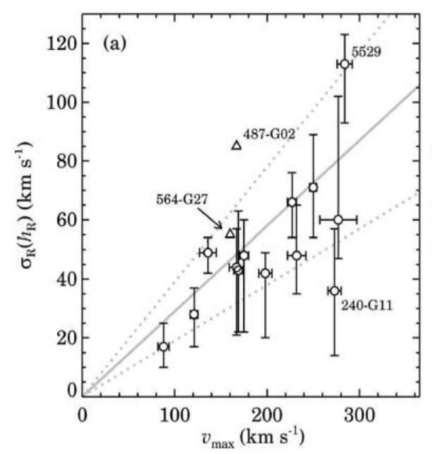
- There is a relation between a fiducial value of the velocity dispersion[16] and the integrated luminosity or the rotation velocity (equivalent through the Tully-Fisher relation).[17]
- This has been confirmed[18].
- The best fit is

$$\sigma_{z|0} = \sigma_{R|1h} = (0.29 \pm 0.10)\, V_{rot}.$$

- Interestingly, the scatter in this relation is not random.

[16] Either the vertical one measured at or extrapolated to the center or the radial velocity dispersion at one schalelength
[17] R. Bottema, A&A 275, 16 (1993)
[18] M. Kregel, P.C. van der Kruit & K.C. Freeman, MNRAS 358, 503 (2005)

- Galaxies below the relation (with lower velocity dispersions) have higher flattening, lower central surface brightness and lower dynamical mass ($4hV_{\rm rot}^2/G$) to disk luminosity ratio.

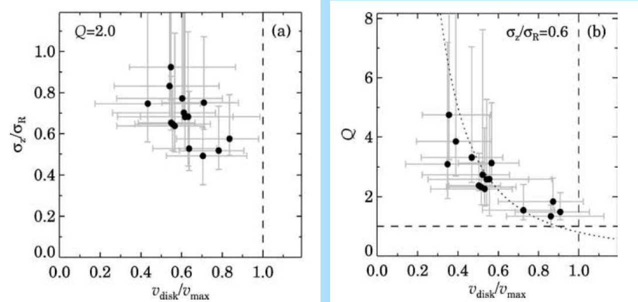


- The linear $\sigma - V_{\rm rot}$ relation follows from straightforward arguments[19].
- Evaluate properties at one radial scalelength ($R = 1h$) and assume a flat rotation curve.
- With an exponential disk and the definition of Q, eliminating h using a Tully-Fisher relation $L_{\rm disk} \propto V_{\rm rot}^4$, results in

$$\sigma_{\rm R} \propto Q \left(\frac{M}{L}\right)_{\rm disk} \mu_0^{1/2} V_{\rm rot}.$$

- When Q and M/L are constant among galaxies, the Bottema relation results and galaxy disks with lower (face-on) central surface brightness $\mu_\circ$ have lower stellar velocity dispersions than the mean.

[19] P.C. van der Kruit, Chapter 10 in 'The Milky Way as a Galaxy' (1990)



The values for Q and $\sigma_\mathrm{z}/\sigma_\mathrm{R}$ are related.
From simple arguments this relates to the flattening[20].

$$\frac{h}{h_\mathrm{z}} \propto Q \left(\frac{\sigma_\mathrm{R}}{\sigma_\mathrm{z}}\right) \sigma_\mathrm{z}^{-1} V_\mathrm{rot} \propto Q \left(\frac{\sigma_\mathrm{R}}{\sigma_\mathrm{z}}\right).$$

[20] P.C. van der Kruit & R. de Grijs, A&A 352, 129 (1999)

- Secular evolution or disk heating results from scattering of stars by
  - Giant Molecular Clouds[21]
  - Spiral irregularities[22]
- The second (which has a larger scale) scatters much less in z.
- The relative importance of these two determines $\sigma_{\mathrm{z}}/\sigma_{\mathrm{R}}$[23].
- Flat galaxies result when the spiral irregularities scatter more efficiently than GMCs.

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[21] Spitzer & M. Schwarzschild M., Ap.J. 114, 385 (1951)
[22] B. Barbanis & L. Woltjer L., Ap.J. 150, 461 (1967)
[23] A. Jenkins & J. Binney, MNRAS 245, 305 (1990)

Maximum disk

- The thickness of the gas layer in a disk galaxy can also be used to measure the surface density of the disk.
- For a density distribution of the exponential, locally isothermal disk and an HI velocity dispersion $\langle V_{\rm z}^2 \rangle_{\rm HI}^{1/2}$ independent of radius[24] and isotropic, and if the stars dominate the gravitational field, the HI layer has a FWHM (to $\lesssim 3\%$) of

$$W_{\rm HI} = 1.7 \langle V_{\rm z}^2 \rangle_{\rm HI}^{1/2} \left[\frac{\pi G (M/L) \mu_\circ}{z_\circ} \right]^{-1/2} \exp\left(R/2h\right).$$

- So the HI layer flares exponentially with an e-folding $2h$.

[24] As e.g. in the face-on spiral NGC 628; G.S. Shostak & P.C. van der Kruit, A&A 132, 20 (1984)

- In the 'maximum disk hypothesis' the disk contribution to the gravitational field is optimized.
- A working definition is that for maximum disk we require[25]

$$V_{\rm disk}/V_{\rm rot} = 0.85 \pm 0.10.$$

- For an exponential disk and using hydrostatic equilibrium and the Bottema relation we find[26]

$$\frac{V_{\rm disk}}{V_{\rm rot}} = (0.21 \pm 0.08)\sqrt{\frac{h}{h_{\rm z}}}.$$

- So we can estimate $V_{\rm disk}/V_{\rm rot}$ from a statistical value for the flattening.

[25] P.D. Sackett, Ap.J. 483, 103 (1997)

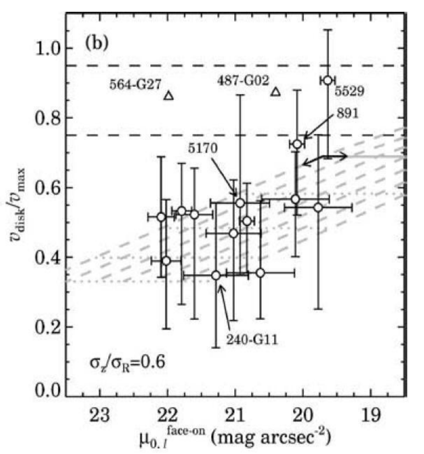
[26] R. Bottema, A&A 275, 16 (1993); P.C. van der Kruit & R. de Grijs, A&A 352, 129 (1999)

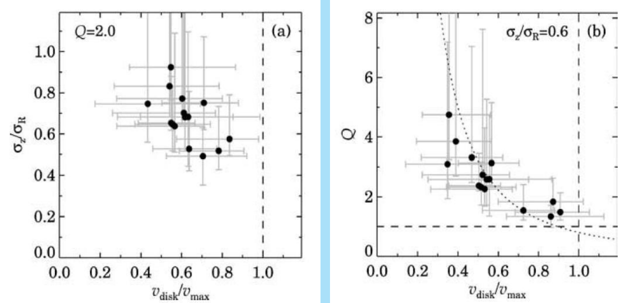
The remarkable thing is that all determinations of the property $V_{\rm disk}/V_{\rm rot}$ from HI flaring and stellar dynamics have been consistent.

NGC891 (HI-layer)[27]	0.62 ± 0.15	$(\frac{140\pm30}{225\pm10})$
Stellar kinematics[28]	0.6 ± 0.2	$(Y = 1.0 \pm 0.3)$
Stellar kinematics[29]	0.63 ± 0.15	
Stellar kinematics[30]	0.53 ± 0.15	
Our Galaxy	0.69 ± 0.15	$(\frac{155\pm30}{225\pm10})$

[27] P.C. van der Kruit, A&A 99, 298 (1981)
[28] P.C. van der Kruit & K.C. Freeman, Ap.J. 303, 556 (1986)
[29] R. Bottema, A.&A. 275 16 (1993)
[30] M. Kregel, P.C. van der Kruit & K.C. Freeman, MNRAS 358, 503 (2005)

- Here we see the values for the individual galaxies in de Kregel et al. sample.
- Most galaxies are not ‘maximum-disk’.

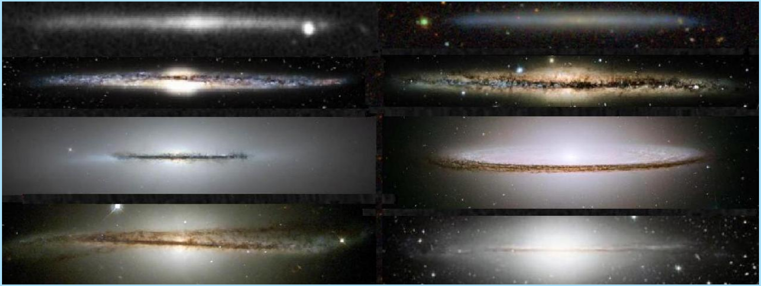




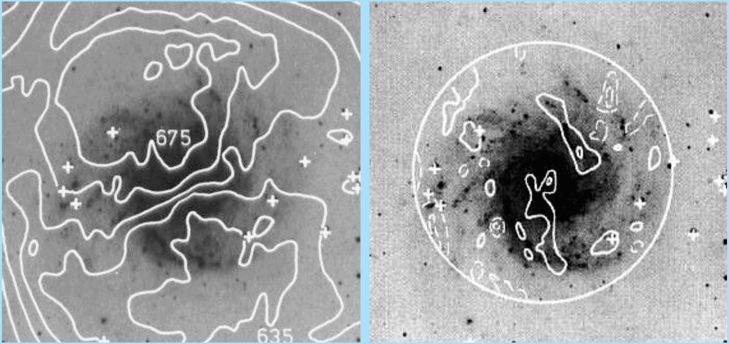
The galaxies that may be maximum disk have a high surface density and appear to have more anisotropic velocity distributions or are less stable according to Toomre Q.

Truncations

Stellar disks are often remarkably flat.



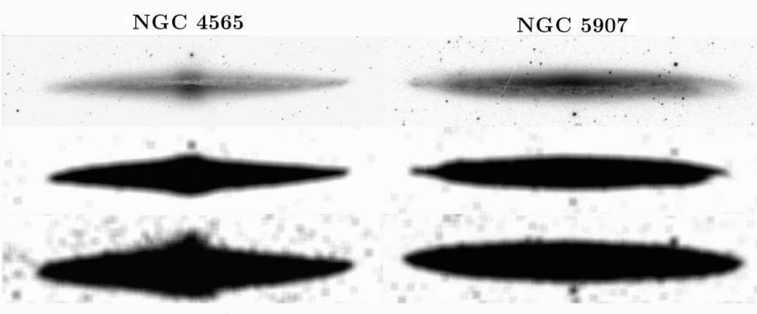
Residual velocity field of NGC 628 (contours 4 and 8 km/s)[31].



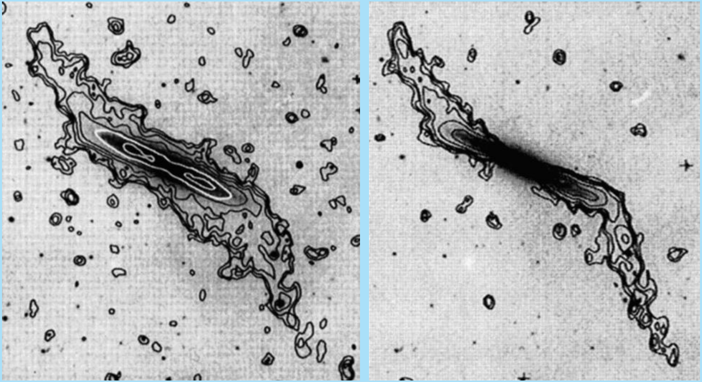
R.m.s. of residuals is 4 km/s or $\sim$ 40 pc in 10^7 years.

[31] G. S. Shostak & P.C. van der Kruit, A&A 132, 20 (1984)

Edge-on galaxies have relatively sharp truncations.



The truncations of the stellar disks appear related to warps in the HI-layers.[32]



[32] P.C. van der Kruit, A&A 396, 173 (2008)

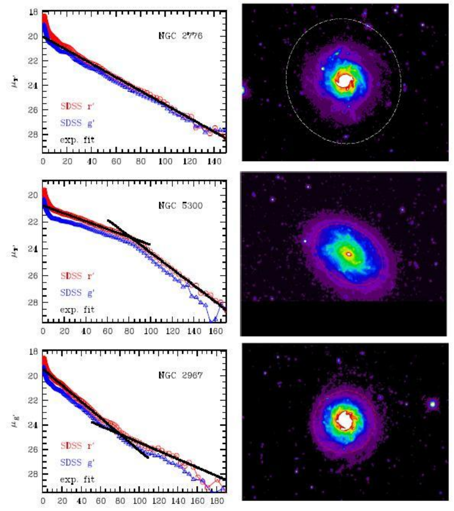
- There is no time to discuss possible origins of truncations and warps[33].
- Extensive work has been performed by Michael Pohlen and collaborators.
- A sample of moderately inclined systems[34] has been studied through ellipse-fitting of isophotes in SDSS data.
- A few edge-on systems[35] have been studied using a decomposition technique.

[33] See e.g. P.C. van der Kruit, A&A 396, 173 (2008)
[34] M. Pohlen & I. Trujillo, A.&A. 454, 759 (2006)
[35] M. Pohlen, S. Zaroubi, R.F. Peletier & R.-J. Dettmar, MNRAS 378, 594 (2007)

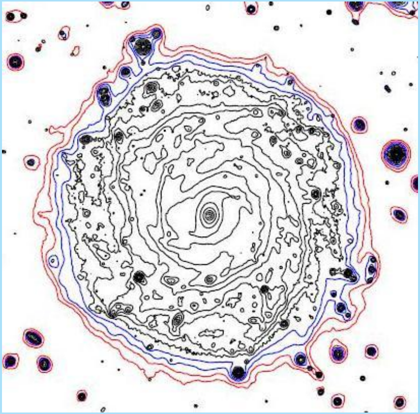
Pohlen & Trujillo distinguish three types of truncations:

- Type I: no break
- Type II: downbending break
- Type III: upbending break

But there are problems with face-on or moderately inclined galaxies as a result of lack of precise axisymmetry.



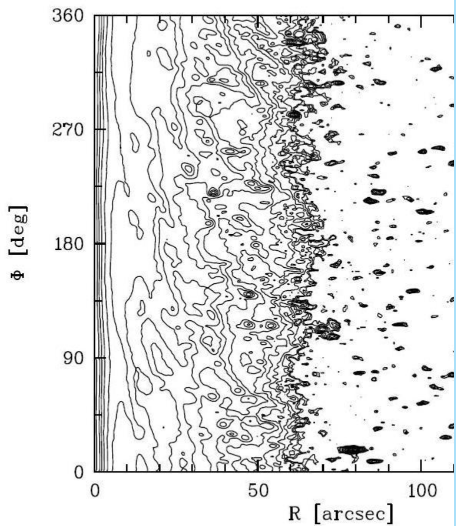
The effects is seen here as well in the red and blue contours of NGC 5923.[36]



[36] M. Pohlen, R.-J. Dettmar, R. Lütticke & G. Aronica, A.&A. 392, 807 (2002)

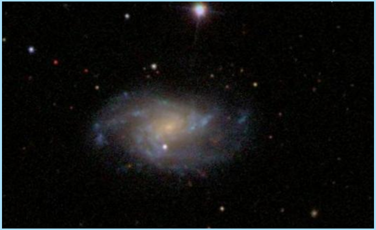
Here is the same data in polar coordinates.

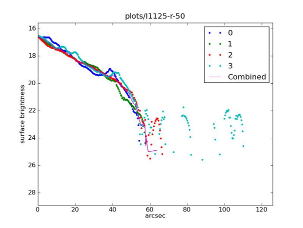
The irregular outline shows that some smoothing out will occur contrary to observations in edge-on systems.

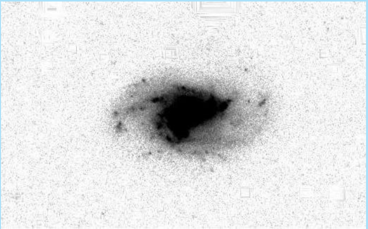


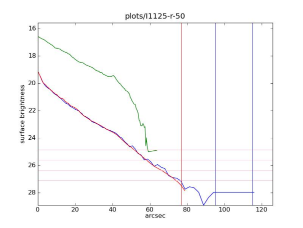
- Stephan Peters (student of Ken and me) together with Roelof de Jong have re-analysed the Pohlen et al. data.
- One way was to mimick edge-on view by collapsing the data onto the major axis.
- Secondly, we calculated a radial profile using equivalent profiles.
- The procedures allow for a 'dynamic smooth' of the data (more smoothing at faint levels).
- There are significant problems with the background level in the SDSS frames.
- I show three examples.

IC 1125
Type I

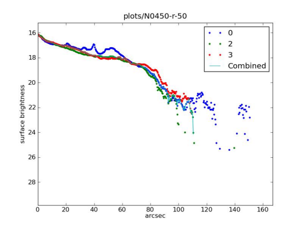


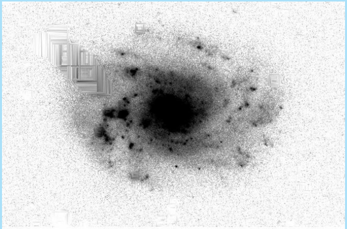


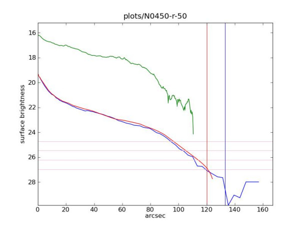




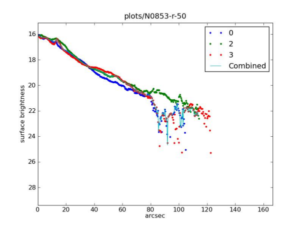
NGC 450
Type II

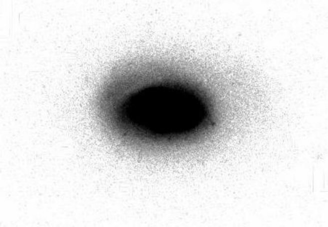


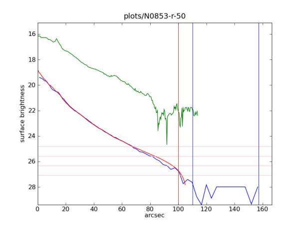




NGC 853
Type III

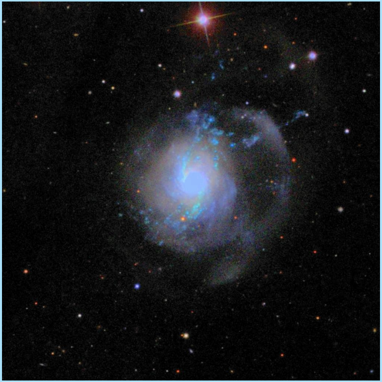






- The radial profiles from ellipse fitting and equivalent profiles agree well.
- The difference is that ellipse fitting assumes a position for the center, the method with equivalent profiles does not.
- Often the major-axis-collapse method shows in Types I *and* II truncations when seen ‘edge-on’.
- There are truncations in the stellar disks but less symmetric than one might expect.
- Type III galaxies do not show ’edge-on truncations’, but invariably evidence for interaction or other disturbances of the outer parts.

E.g. NGC 3310 is a Type III according to Pohlen & Trujillo!



Conclusions

- Vertical stellar velocity dispersions show that in most galaxies M/L is constant with radius.
- Most galaxies have $Q \sim 2$.
- Various methods lead to a consistent picture that most galaxies are sub-maximal.
- Maximum disk galaxies have relatively high surface brightness and have more anisotropic velocity distributions and/or have smaller values for Q.
- Stellar disks are very flat.
- Truncations are common, but disks deviate from precise axial symmetry. Pohlen et al.'s Type III are distorted or interacting systems.