Letter to the Editor

Cut-off radii of galactic disks

A new statistical study on the truncation of galactic disks [*]

M. Pohlen, R.-J. Dettmar, and R. Lütticke

Ruhr-Universität Bochum, Astronomisches Institut, 44780 Bochum, Germany (pohlen,dettmar,luett@astro.ruhr-uni-bochum.de)

Abstract. We present the analysis of a CCD survey of 31 nearby (≤ 110 Mpc) edge-on spiral galaxies. The three-dimensional one-component best fit models provide their disk-scalelengths h and for the first time their disk cut-off radii $R_{\rm co}$. We confirm for this sample the existence of such sharp truncations, and find a significantly lower mean value of the distance independent ratio $R_{\rm co}/h = 2.9 \pm 0.7$ than the standard value of 4.5 often used in the literature. Our data show no correlation of these parameters with Hubble type, whereas we report a correlation between $R_{\rm co}/h$ and the distance based scalelength in linear units. Compared to the Milky Way we find only lower values of $R_{\rm co}/h$, explained either by possible selection effects or by the completely different techniques used. We discuss our data in respect to present models for the origin of the cut-off radii, either as a relict of the galaxy formation process, or as an evolutionary phenomenon.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: photometry – galaxies: structure – galaxies: spiral

1. Introduction

Although *cut-off radii* of spiral galaxies are known for about 20 years no unique physical explanation has been given to describe this observational phenomenon. They were already mentioned by van der Kruit (1979), who stated, based on photographic material, that the outer parts of disks of spiral galaxies "do not retain their exponential light distribution to such faint levels", whereas the exponential behaviour of the radial light distribution for the inner part was well accepted (de Vaucouleurs 1959, Freeman 1970). For three nearby edge-on galaxies he claimed, that the typical radial scalelength h steepens from 5 kpc to about 1.6 kpc at the edge of the disk. This is confirmed by modern deep CCD imaging (Abe et al. 1999, Fry et al. 1999, Näslund & Jörsäter 1997). In a fundamental series of papers van der Kruit & Searle

(1981a, 1981b, 1982a, 1982b) determined a three dimensional model for the luminosity density of the old disk population taking into account these sharp truncations at the *cut-off radius* $R_{\rm co}$. They applied their model of a locally isothermal, selfgravitating, and truncated exponential disk to a sample of seven edge-on galaxies and found that all disks show a relatively sharp cut-off where the scalelength h suddenly drops below 1 kpc, starting at radii of $(4.2 \pm 0.5)h$. The *cut-off radius* of edge-on galaxies is detected at levels of 24-25 mag/$\square''$ which is about 2-3 mag brighter compared to face-on disks due to the integration along the line of sight. Therefore van der Kruit & Shostak (1982) and Shostak & van der Kruit (1984) quote the only known cut-offs in the literature for face-on galaxies. In addition to the much lower brightness one has to deal with intrinsic deviations from the circular symmetry of the disk, for example from the young stellar population, hidden by an azimuthally averaged profile. In a subsequent paper van der Kruit (1988) stated that out of the 20 face-on galaxies observed by Wevers et al. (1986) only four did not show any sign for a drop off as judged from the last three contours. Barteldrees & Dettmar (1989) confirmed for the first time the existence of these truncations for a larger sample of edge-on galaxies using CCD surface photometry refining the previous photographic measurements.

These truncations are not the boundary of the galactic baryonic mass distribution, but such 'optical edges' suggest dynamical consequences for the interpretation of observed rotation curves (Casertano 1983), as well as for the explanation of warped disks (Bottema 1995). Their sharpness restrict the radial velocity dispersion at the edge of the disk (van der Kruit & Searle 1981a), and will therefore have important implication for viscous disk evolution (Thon & Meusinger 1998). According to Zhang & Wyse (2000) the disk cut-off radii constrain the specific angular momentum in a viscous galaxy evolution scenario.

In this letter we report the largest sample of well defined cut-off radii for edge-on galaxies derived by CCD surface photometry. Our sample (Pohlen et al. 2000, Paper II) comprises 31 galaxies, including the 17 galaxies of Barteldrees & Dettmar (1994, hereafter Paper I). Thereby we are able to derive first statistical conclusions and determine general correlations with

---

other characteristic galaxy parameters in order to approach in the future a physical model explaining the observed phenomenon.

2. Observations and reduction

Sample selection, observations, and data reduction are described in detail in Paper I and II, and will be repeated only briefly here. We have compiled a homogeneous set of 31 galaxies with well defined models of their three-dimensional disk luminosity distribution, out of our sample of about 60 highly inclined disk galaxies, selected from the UGC (Nilson 1973) and ESO-Lauberts & Valentijn (1989) catalog. The data were obtained at the ESO/La Silla 2.2m and the Lowell Observatory 42-inch telescope. Images are taken either in Gunn g, r, i, or Johnson R filters, with resulting pixel scales of $0.36''$ and $0.7''$, respectively. After standard reduction, images were rotated to the major axes of the disk. Although most of the images were taken during non-photometric nights we have tried to perform photometric calibration for each image by comparing simulated aperture measurements with published integrated aperture data, resulting in the best possible homogeneous calibration for the whole sample. The resulting typical values for the limiting surface brightness measured by a three sigma deviation on the background are: $\mu_{\mathrm{g}} \approx 25 \mathrm{mag}/\square''$, $\mu_{\mathrm{R,r}} \approx 24.5 \mathrm{mag}/\square''$, and $\mu_{\mathrm{i}} \approx 23.5 \mathrm{mag}/\square''$. In order to obtain absolute values of the determined structural parameters, we estimated the distance of our galaxies according to the Hubble relation ($H_0 = 75 \, \mathrm{km \, s^{-1} Mpc^{-1}}$) using published heliocentric radial velocities corrected for the Virgo centric infall.

3. Analysis

3.1. Disk model and fitting

Our model, as described in detail in Paper I and II, for the three-dimensional luminosity distribution for galactic disks is based upon the fundamental work of van der Kruit and Searle (1981a):

$$\hat{L}(R,z) = \hat{L}_0 \, \exp\left(-\frac{R}{h}\right) f_n(z, z_0) \, \mathrm{H}(R_{\mathrm{co}} - R) \qquad (1)$$

$\hat{L}_0$ is the central luminosity density in units of $[L_\odot \, \mathrm{pc}^{-3}]$, R and z are the radial resp. vertical axes in cylindrical coordinates, h is the radial scalelength, and z_0 the scaleheight. $f_n(z, z_0)$ describes three different fitting functions for the vertical distribution: exponential, sech, and the physically motivated isothermal (sech^2) case (van der Kruit 1988). R_{co} is the cut-off radius, where the stellar luminosity density is assumed to be zero outside, mathematically expressed by a Heaviside function $\mathrm{H}(x_0 - x)$. These radii are defined at the position where the radial profiles bend nearly vertical into the noise, whereby a mean value is taken for the two different sides.

Depending on the inclination angle i, we numerically integrate this 3D-model along the line of sight and compare the two-dimensional result with the observed CCD image, leading to six free fitting parameters: the inclination i, the central luminosity density $\hat{L}_0$, the scalelength h, and -height z_0, the cut-off
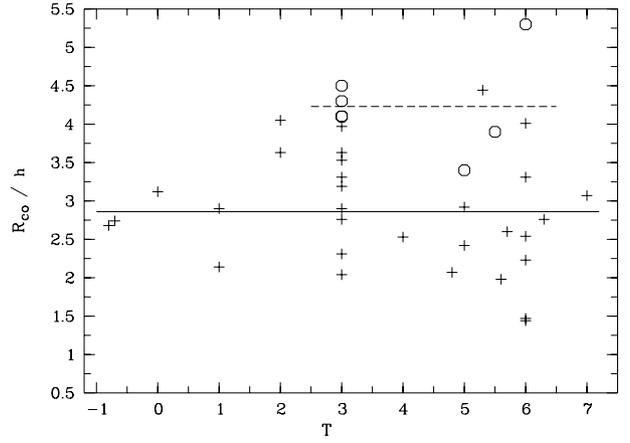

Fig. 1. Ratio of cut-off radius to radial scalelength versus morphological type T. The 31 galaxies from our sample are marked by a cross, whereas the circles are the values for 7 galaxies from van der Kruit & Searle (1982a). The dashed line represents their and the solid line our mean value.

radius R_{co}, and the function for the z-distribution $f_n(z, z_0)$. After our discussion about two different fitting methods in Paper II, we finally used our implemented "downhill simplex-method" (Nelder & Mead, 1965) to minimize the difference between model and observed disk. The possible influence of these parameters on the neglected dust distribution is estimated in Paper II.

4. Results

4.1. Distribution of cut-off radii

Understanding the phenomenon of cut-off radii in galactic disk requires as an essential step a statistical study of galaxies covering the Hubble sequence. Fig. 1 shows, already suggested by Barteldrees & Dettmar (1989) for a smaller sample of 20 galaxies, that the distance independent ratio of cut-off radius to radial scalelength is significantly lower than derived from the often referred sample of van der Kruit & Searle (1982a) with 7 galaxies. They reported a mean value of $R_{\mathrm{co}}/h = 4.2 \pm 0.5$ (ranging from 3.4 to 5.3), whereas our sample gives a ratio of $R_{\mathrm{co}}/h = 2.9 \pm 0.7$ ($1.4-4.4$) even below their minimal value. As obvious from Fig. 1 this difference is not caused by the larger range of Hubble types covered by our sample. The estimated error for this ratio due to the selection of the best fitting model described in Paper II is ± 0.6 and has the same order as the quoted standard deviation. As shown in Paper II for two different dust distributions with values observed by Xilouris et al. (1999), the influence of the neglected dust on our fitting process will be an overestimation of the scalelength h, whereas R_{co} is independent. For the *worst* case, defined by the largest measured values for h_{d}/h_*, z_{d}/z_*, and τ_{R}, we find that this will chance our values for R_{co}/h by $+0.5$. Applied to the mean we are in this case still 0.8 below the value of van der Kruit & Searle (1982a). We do not find a correlation between R_{co}/h and the Hubble type, although it should be mentioned that in general
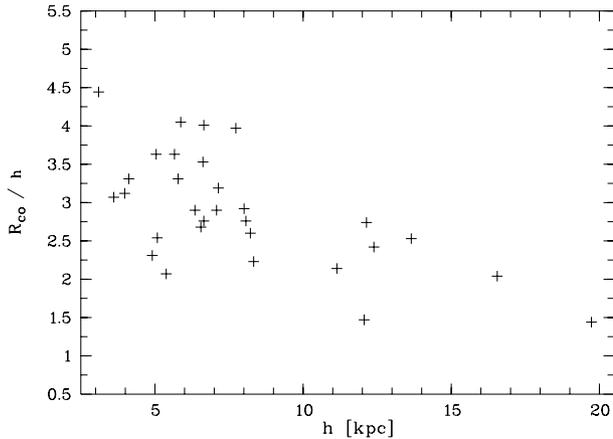
Fig. 2. Ratio of cut-off radius to radial scalelength versus scalelength in absolute units for the 30 galaxies with measured radial velocities.

for galaxies later than Scd the fitting process is strongly affected by intrinsic variation, e.g. individual bright HII-regions, which makes it impossible to fit our simple symmetric model. On the other side some early type galaxies and particularly lenticulars do not show any evidence for a cut-off at all. This is already suggested by van der Kruit (1988) observing some early type face-on galaxies and will be discussed in detail in a forthcoming paper.

Fig. 2 shows a possible correlation between R_{co}/h and the scalelength in absolute units: *Large disks with regard to their scalelengths h are short in terms of their cut-off radii.* Together with the fact that the cut-off occurs, within the errors of ± 0.5 mag, at nearly the same surface brightness level, this can be explained with a correlation between the central surface brightness and the scalelength of the galaxy, recently proposed by Scorza & van den Bosch (1998) for galactic disks of different sizes.

4.2. Comparison with literature

For the 30 galaxies with known radial velocities we find values for the scalelength of 3.1 up to 19.7 kpc with a median of 6.6 kpc. Van der Kruit (1987) determines for a diameter limited sample of 51 galaxies scalelengths in the range of $0.7 - 9.2$ kpc with a maximum of the distribution at about 3 kpc. De Jong (1996) derives for his sample of 86 face-on galaxies transformed to our H_0 a range of $1.0 - 14.4$ kpc with a median around 3.0 kpc, whereas Courteau (1996) finds for 290 Sb-Sc galaxies a range of $0.5 - 9.6$ kpc with a maximum at 3.9 kpc; reduced to our H_0. In agreement with de Jong (1996) we do not find a correlation of the scalelength with the Hubble type.

We find cut-off radii from $11.1 - 34.5$ kpc with a median at 20.2 kpc, compared to the only available sample of cut-off radii by van der Kruit & Searle (1982a) with $7.8 - 24.9$ kpc for their 7 investigated galaxies. Although we do not find a tight correlation between catalogued surface brightness radii, e.g. D_{25}, and our cut-off radii, they can be used to compare the sizes of the galaxies within our sample. Rubin et al. (1980)

study 21 Sc galaxies, where they claim radii, characterized by the radius at the D_{25} contour reduced to our H_0, of 81.3 kpc and 35.3 kpc for the two biggest ones, and Romanishin (1983) finds values of $30 - 73$ kpc for 107 intrinsically large spiral galaxies.

We find a clear correlation between the determined cut-off radius and the distance of the galaxy. This implies that we pick intrinsically large galaxies at higher distances due to our selection criterion which is based on the angular diameter matching the filed of view.

4.3. Comparison with the Milky Way

It is of particular interest to compare our statistical result with the structural parameters derived for the Milky Way. Robin et al. (1992) as well as Ruphy et al. (1996) determine the radial structure of the galactic disk with a synthetic stellar population model using optical and NIR star-counts, respectively. They confirm a sharp truncation of the old stellar disk at 14 ± 0.5 kpc and 15 ± 2 kpc, respectively. Freudenreich (1998) fits a model for the old galactic disk to the NIR data obtained from the survey of the DIRBE experiment also confirms an outer truncation of the disk around 12.4 ± 0.1 kpc. The result of both methods depend directly on the distance to the galactic center ($R_0 = 8.5 \pm 1$ kpc). These values are in agreement with the findings of Heyer et al. (1998), who measure a sharp decline in the CO mass surface density and conclude that the molecular disk is effectively truncated at $R = 13.5$ kpc.

In contrast to former investigations (van der Kruit 1986, Lewis & Freeman 1989, Nikolaev & Weinberg 1997) placing the Milky Way scalelength around $4 - 5.5$ kpc, Robin et al. (1992), Ruphy et al. (1996), and Freudenreich (1998) quote significantly lower scalelengths of 2.5 ± 0.3 kpc, 2.3 ± 0.1 kpc, and 2.59 ± 0.02 kpc, respectively. This leads to values of 5.6 ± 0.5, 6.5 ± 1.2, and 4.8 ± 0.1 for R_{co}/h. Whereas the first two values are significantly higher than any value found in our sample (even the highest value of van der Kruit & Searle is only 5.3) the latter determination by Freudenreich is consistent with our highest value of 4.4 within the errors.

If the Milky Way is a 'typical' galaxy with $R_{co}/h = 2.9$ the scalelength should be expected to be $h \geq 4.1$ kpc for $R_{co} \geq 12$ kpc.

4.4. Comparison with models

Only few theoretical models can be found in the literature addressing a physical description for the origin of cut-off radii.

Taking into account a basic picture of galaxy formation, starting with a rotating protocloud, Seiden et al. (1984) explain in their framework of a stochastic, self-propagating star-formation theory (SSPSF) several properties of galactic disks. The crucial point is, that they assume a $1/R$ dependence instead of an exponential law for the total surface density. In this case they show that a feature similar to a cut-off radius automatically appears in the radial profile, which is directly linked with the scalelength. This is in contrast to Fig. 2, where R_{co} and h vary independently.

Van der Kruit & Searle (1981a) proposed that within a scenario of slow disk formation (Larson 1976) this radius might be that radius where disk formation time equals the present age of the galaxy. This isolated slow evolution is in contradiction to recent models preferring interaction and merging as a driver for galaxy evolution (Barnes 1999).

Later van der Kruit (1987) proposed a working hypotheses which already includes some of the currently accepted ingredients for galaxy formation to explain the truncation as a result of the formation process. Galactic disks develop from collapsing, rotating proto-clouds. After the dark matter has settled into an isothermal sphere first star-formation in the center builds up a bulge component and the remaining material settles in gaseous form with dissipation in a flat disk under conservation of specific angular momentum. This leads to a constant value for R_{co}/h of 4.5, which is in contrast to our observations.

In a recent paper about galaxy formation and viscous evolution Zhang & Wyse (2000) additionally consider a self-consistent description of the disk-halo system by dropping the assumption of a static halo and find that the disk cut-off radii indeed constrain the specific angular momentum.

Kennicutt (1989) shows that for a sample of 15 face-on spiral galaxies, analysing HI, CO and H_α data, star-formation stops below a critical threshold value, which is associated with large scale gravitational instabilities. Taking into account the dynamical critical gas density Σ_{crit} for a thin, rotating, isothermal gas disk proposed by Toomre (1964) he observes the abrupt decrease in star-formation at a radius where the measured gas density drops below Σ_{crit}. In the case of NGC 628 this radius coincides with R_{co} determined by Shostak & van der Kruit (1984).

Although it is still unknown if the cut-off radius is an evolutionary phenomenon or has its origin in the galaxy formation process a star-formation threshold at the 'optical edge' seems to be a promising approach to address this problem (Elmegreen & Parravano 1994, and references therein; Ferguson et al. 1998). This will be done in the future by enlarging the sample with a better defined selection criterion which also includes the environment.

References

Abe F. et al. (The MOA Collaboration), 1999, AJ 118, 261

Barnes J.E., 1999, in: The Evolution of Galaxies on Cosmological Timescales, Beckman J.E., Mahoney T.J. (eds.), ASP Conference Series, in press

Barteldrees A., Dettmar R.-J., 1989, in: Dynamics and Interaction of Galaxies, Wielen R. (ed.), Springer-Verlag, Heidelberg, p. 348

Barteldrees A., Dettmar R.-J., 1994, A&AS 103, 475 (Paper I)

Bottema R., 1995, A&A 295, 604

Casertano S., 1983, MNRAS 203, 735

Courteau S., 1996, ApJS 103, 363

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

de Vaucouleurs G., 1959, in: Handbuch der Physik LIII, ed. Flügge S., Springer-Verlag Berlin, p. 275

Elmegreen B.G., Parravano A., 1994, ApJ 435, L121

Ferguson A.M.N., Wyse R.F.G., Gallagher J.S., Hunter D.A., 1998, ApJ 506, L19

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

Freudenreich H.T., 1998, ApJ 492, 495

Fry A.M., Morrison H.L., Harding P., Boroson T.A., 1999, AJ 118, 1209

Heyer M.H., Brunt C., Snell R.L., Howe J.E., Schloerb F.P., Carpenter J.M., 1998, ApJS 115, 241

Kennicutt R.C., 1989, ApJ 344, 685

Larson R.B., 1976, MNRAS 176, 31

Lauberts A., Valentijn E.A., 1989, The surface photometry catalogue of the ESO-Uppsala galaxies, European Southern Observatory, Garching

Lewis J.R., Freeman K.C., 1989, AJ 97, 193

Näslund M., Jörsäter S., 1997, A&A 325, 915

Nelder J.A., Mead R., 1965, Computer Journal, Vol. 7, p. 308

Nikolaev S., Weinberg M.D., 1997, ApJ 487, 885

Nilson P., 1973, Uppsala General Catalogue of Galaxies, Uppsala

Pohlen M., Dettmar R.-J., Lütticke R., Schwarzkopf U., 2000, submitted to A&AS (Paper II)

Robin A.C., Creze M., Mohan V., 1992, ApJ 400, L25

Romanishin W., 1983, MNRAS 204, 909

Rubin V.C., Thonnard N., Ford W.K. JR., 1980, ApJ 238, 471

Ruphy S., Robin A.C., Epchtein N., Copet E., Bertin E., Fouqué P., Guglielmo F., 1996, A&A 313, L21

Scorza C., van den Bosch F.C., 1998, MNRAS 300, 469

Seiden P.E., Schulman L.S., Elmegreen B.G., 1984, ApJ 282, 95

Shostak G.S., van der Kruit P.C., 1984, A&A 132, 20

Thon R., Meusinger H., 1998, A&A 338, 413

Toomre A., 1964, ApJ 139, 1217

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

van der Kruit P.C., 1986, A&A 157, 230

van der Kruit P.C., 1987, A&A 173, 59

van der Kruit P.C., 1988, A&A 192, 117

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

van der Kruit P.C., Searle, L., 1981b, A&A 95, 116

van der Kruit P.C., Searle, L., 1982a, A&A 110, 61

van der Kruit P.C., Searle, L., 1982b, A&A 110, 79

van der Kruit P.C., Shostak G.S., 1982, A&A 105, 351

Wevers B.M.H.R., van der Kruit P.C., Allen R.J., 1986, A&AS 66, 505

Xilouris E.M., Byun Y.I., Kylafis N.D., Paleologou E.V., Papamastorakis P., 1999 A&A 344, 868

Zhang B., Wyse R.F.G., 2000, astro-ph/0002213, accepted for publication in MNRAS 2000