Edge-on disk galaxies

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Chapter 10 | *Summary and Prospects*

Abstract. In this concluding Chapter I summarize the results obtained in this Ph.D. thesis from the study of the multi-passband optical and near-infrared surface photometry of a statistically complete sample of edge-on disk galaxies and discuss a number of possible applications for future research in this field.
The main scientifically interesting questions that have been addressed are the nature of the vertical stellar distribution in galaxy disks, the effects of dust in edge-on galaxies, and the occurrence of optical warps at the outer edges of the galaxy disks.

In this Chapter I summarize the results of the *B, V, I, J,* and K'-band multiwavelength study of 48 highly inclined, undisturbed disk galaxies on the southern sky, as well as related results obtained from pilot studies of northern-hemisphere edge-on galaxies. The optical and near-infrared observations obtained for this Ph.D. Thesis research project currently represent the largest sample of its kind available for which high quality and accurate surface photometry has been obtained (Chapter 2).

A number of scientifically interesting questions concerning the structure of the stellar disks of galaxies have been addressed. In particular, the vertical stellar distribution in galaxy disks, the effects of dust in edge-on galaxies, and the peculiar behaviour of the outer galaxy disks, like the occurrence of optical warps and the radial dependence of the exponential scale height, have been studied in detail.

1 Overview of results

1.1 Vertical disk structures and the effects of extinction

We have attempted to follow the K'-band vertical luminosity distributions all the way down to the galaxy planes by studying (near-infrared) K'-band observations of a random subsample of 24 disk galaxies (Chapter 8). In the majority of our sample galaxies we find that *the luminosity peak of the K'-band vertical light profiles is only slightly rounder than expected for an exponentially decreasing light distribution.*

Since projection effects cause a sharply-peaked profile to be flattened towards the galaxy plane, our result is consistent with the hypothesis that all spiral galaxies have exponential vertical luminosity profiles.

The fact that we observe this in *all* our sample galaxies, and that the effect is independent of position along the galaxies' major axes, indicates that *the process responsible for this effect is intrinsic to the disks themselves, and both global (within a specific galaxy) and universal (among disk galaxies) in nature.*

This observation puts strong constraints on the *vertical heating mechanisms* of galaxy disks. For instance, the popular theory that spiral galaxies are heated by the combined effects of spiral arms and the Giant Molecular Clouds is hard to reconcile with the observations of the global nature of our vertical luminosity profiles.

We chose to study the vertical luminosity profiles in the K' band, since K'-band observations are relatively insensitive to contamination by young stellar populations and galactic dust. However, the effects of dust are not completely negligible, even at those (relatively long) wavelengths. The K'-band light is likely dominated by the old disk, and the young population is relatively unimportant. Moreover, the mass-to-light ratio is almost independent of metallicity and age in this passband. Therefore, since neither dust nor young, luminous red stars strongly affect the K' band, imaging in this passband is a reliable and efficient method to map surface mass variations through surface brightness fluctuations.

1.2 Colours and colour gradients in edge-on galaxies

Once away from the central dust lane, the *I–K* colours of the (old) disk component are remarkably constant and featureless (Chapter 8). Therefore, we have defined "dust-free" *I–K* colours, which can be used to construct an optical/near-infrared colour – absolute magnitude (CM) diagram for spiral galaxies, similar to one found for elliptical galaxies (Chapter 6).

This relationship is a potentially powerful tool that can be used as a *secondary distance indicator.* The errors in the derived distances are comparable to those obtained from the *K*-band Tully-Fisher relation (TFR), and only slightly larger than those in the *I*-band TFR. The intrinsic scatter in the CM relation (~ 0.5 mag in absolute magnitude) puts a lower limit to the accuracy of distance determinations of $\sim 25\%$, for galaxies brighter than $M_K \sim -25$.

Based on scale length ratios, we show that the radial colour gradients between optical (*B*-band) and near-infrared passbands are considerable, even at 1.0 – 1.5 scale heights from the galaxy planes (Chapter 5). We show that any significant deviation from unity of the scale length ratios is *completely dominated by dust effects.*

The vertical scale parameters, obtained between 1.5 and 3.5 scale heights, are independent of passband, indicating that they trace the old-disk population (which is rather uniform in colour).

It appears that the ratio between scale length and disk thickness is a function of galaxy type (Chapter 5). The correlation is in the sense that *the flattening of galaxy disks increases from the early-type disk galaxies to at least Sc-type galaxies.* The average flattening is more or less constant for the later types (types Scd and later).

1.3 Peculiarities in the outer disks

We present the discovery of a thick disk in NGC 6504 (Chapter 3); this is one of the first clear detections of a thick disk in a spiral galaxy. We also detected thick disks in the earliest-type sample galaxies of our southern-hemisphere sample, which are likely the cause of the *increasing scale height as a function of (projected) galactocentric distance* in a number of our sample galaxies (Chapter 7).

The effect is most noticeable in the earliest-type sample galaxies, where the increase of the scale height may be up to a factor of 1.5 in the outer disk regions. However, *to first order the scale height of the later-type galaxies is constant*, although even for those types a trend of "flaring" can be inferred from the observations (Chapters 4 and 7).

A detailed study of stellar warps (Chapter 9) shows that *the frequency of optical warps is comparable to that observed in HI 21cm observations*; the frequency of observed optical warps is consistent with an actual frequency of close to 100% of warped stellar galaxy disks. The occurrence of stellar warps does not seem to correlate with galaxy type, size, or compactness.

Based on the observations analysed in Chapter 9, we cannot confirm the hypothesis that warps are induced by magnetic fields or gas pressure, although we cannot completely discard this possibility either. Due to the large frequency of warped isolated field galaxies and the symmetrical warps detected in a number of galaxies, gravitational interaction also seems to be ruled out. We argue that "secondary infall" during the lifetime of a galaxy is a likely formation process.

2 Suggestions for future study

Although we have reached a number of conclusions concerning the structure of galaxy disks, my Ph.D. work has raised more questions than we have been able to solve. In this final section I will summarize a few of my suggestions for future work in this field.

2.1 The vertical nature of galaxy disks

In Chapter 7 we presented evidence for an increase of the exponential scale height as a function of (projected) galactocentric distance, which is most noticeable for the earliest-type galaxies. The effect can be understood if early-type disk galaxies have thick disks with both scale lengths and scale heights that are larger than those of the dominant disk component. Its origin appears to be linked to the processes that have formed the thick disk.

However, the origin of the thick disk and its properties are not yet well understood. Even though the observations of the highly-inclined disk galaxies analysed in this Ph.D. Thesis are very well suited to study the thick disk properties, their colours, and their relation to a possible optical counterpart of the dark halo (e.g., Morrison et al., 1994), deeper observations of galaxies with known thick disks will greatly facilitate this study.

Although it has been claimed that thick disks are somehow related to the bulge-disk structure of early-type (S0) galaxies, we have also presented evidence for the presence of a thick disk in the Sab galaxy NGC 6504 (Chapter 3). Therefore, a detailed study of thick disks in both lenticular and spiral galaxies will likely provide strong constraints on the conditions for their presence as well as on their origin.

In Chapter 8 we presented evidence that the vertical luminosity distributions in galaxy disks may obey an exponential law all the way down to the galaxy planes. If the luminosity distributions are really very closely exponential, one expects luminosity cusps in the galaxy planes that are more sharply peaked than exponential. However, these results were based on seeing-limited observations. The average seeing conditions of our observations imply a spatial resolution for our sample galaxies on the order of a few hundred parsecs. Therefore, higher-resolution near-infrared observations (in the H or it K band (or an equivalent wavelength range), obtained with, e.g., the *Hubble Space Telescope (HST)*, or 8m class telescopes, will provide interesting constraints on the luminosity (and perhaps density) cusps expected in the galaxy planes.

Although we have used the near-infrared K'-band data to follow the vertical light distributions all the way down the the galaxy planes, our observations in optical passbands are well-suited for a detailed study of the vertical extinction and dust layering properties in galaxy disks. In the (apparently) larger galaxies, the dust layer shows many small-scale extinction features, some of which can be traced up to a few scale heights out of the plane. Therefore, by studying these features, and their relation to actively star-forming regions, we may be able to study the role of galactic dust in the stellar disk – halo connection (e.g., Howk & Savage, 1997).

2.2 Truncated stellar disks

In a pioneering series of papers, van der Kruit & Searle (1981a,b, 1982a,b) concluded that a reasonably sharply truncated exponential disk was required to account for the radial light distributions in a number of edge-on disk galaxies. These cut-offs are not infinitely sharp edges, but rather regions where the radial exponential scale length suddenly decreases from several kpc to less than ~ 1 kpc. In fact, the sharpness of the disk truncations will have important implications for viscous disk formation scenarios (e.g., Yoshii & Sommer-Larsen, 1989).

A sample of highly inclined disk galaxies like the one analysed in this Ph.D. Thesis is ideal to study the occurrence, the colour dependence and related physical properties of truncated stellar disks. Since the truncations usually occur at very low surface brightness levels, they show up more readily in highly-inclined galaxies, where we can follow the light distributions to larger radii. Moreover, in less highly-inclined systems, the truncations are generally not seen in azimuthally averaged light profiles, due to global asymmetries in the young disk population, such as spiral arms.

A statistical study of these truncation radii may pose interesting constraints on galaxy formation theory. Formation mechanisms that have been proposed incluse both intrinsic physical processes and projection effects due to the projection of spiral arms with respect to the line of sight. The importance of this effect can be assessed observationally, since in this case one would expect and asymmetry in either the occurrence of the truncations themselves or in the truncation lengths on either side of the galaxies.

Intrinsic physical formation mechanisms include

- The collapse of a protogalaxy with a specific angular momentum distribution of a uniformly rotating, uniform density sphere in the gravitational field of a dark halo with a flat rotation curve under detailed conservation of angular momentum (van der Kruit, 1987).

- Alternatively, it was proposed that star formation has ceased at the truncation radius due to the low HI density at that position (e.g., Fall & Efstathiou, 1980; van der Kruit & Searle, 1981a).
- In a scenario with slow disk formation (e.g., Larson, 1976) the truncation radius might be the radius where the disk formation time equals the present age of the galaxy.
- Tidal interactions between neighbouring galaxies may be the cause of sharp disk truncations in individual galaxies, they are not likely responsible for the majority of the observed disk cut-offs (e.g., Bottema, 1995).

2.3 Disk colours and vertical colour gradients

We have shown that spiral galaxies obey a tightly constrained optical/near-infrared CM relation if we use colours that were determined on the essentially dust-free side of our sample galaxies (Chapter 6). This relation can in principle be used for secondary distance estimates. However, due to the observational scatter of ~ 0.5 mag in absolute magnitude, the accuracy of distance determinations based on the CM relation presented in this Ph.D. Thesis is only $\sim 35\%$.

By obtaining high-quality observations of highly-inclined galaxies the accuracy of this method can be improved. The observational scatter can likely be reduced ~ 0.02 mag. The accuracy will thus be limited to $\sim 25\%$ by the intrinsic scatter in the optical/near-infrared CM relation (~ 0.5 mag).

Since the galaxies need to be spatially resolved, high-resolution observations done with, e.g., the *HST*, can provide a powerful tool to minimize the observational scatter and extend the useful distance range. Therefore, such observations are expected to provide the means to calibrate the relationship.

In the discussion of the optical/near-infrared CM relation and its applicability we assumed that the vertical colour gradients in I–K are small or negligible compared to the observational uncertainties, as could be inferred from the vertical I–K colour profiles presented in Chapter 8.

However, because of the high-quality multi-passband observations and the special orientation of our sample galaxies, our sample is ideal to study vertical colour gradients, not only in the I–K colours, but also in colours obtained from other optical and near-infrared passband combinations. Detailed knowledge of vertical colour gradients, combined with knowledge of the shape of the vertical luminosity and mass distribution places strong constraints on the formation and subsequent evolution of the disks of spiral galaxies (e.g., Peletier & Balcells, 1997).

2.4 Dynamics and stability of galaxy disks

An exponential vertical luminosity distribution and possibly a similar mass distribution in galaxy disks puts interesting constraints on the vertical disk dynamics (Chapter 8). In order to really assess the dynamical implications of such mass distributions, one needs to study the face-on velocity fields of disk galaxies.

Furthermore, the observed increasing scale height with (projected) galactocentric distance (Chapter 7) may be related to the stellar velocity dispersion falling more slowly than exponentially, as predicted by the constant Q model (Toomre, 1964). Similarly, a non-exponential behaviour of the stellar velocity dispersion with radius is suggestive of a non-constant disk scale height (under the assumption of a flat rotation curve) or of the presence of a thick disk.

As a subject for further investigation it may be worthwhile to study both the (projected) radial and the vertical velocity dispersion distributions 2-dimensionally in a number of moderately inclined spiral galaxies.

Bertola et al. (1995) and Fisher (1997) find for their samples of early-type disk galaxies that the stellar velocity dispersions may decrease less rapidly than exponentially, along both the major and minor axes. This result is independent of viewing angle and would indicate that the radial and vertical velocity dispersions become more nearly constant with radius.

Van der Kruit & Freeman (1986) and Bottema (1993) have carried out a detailed study of a number of (mainly later-type) disk galaxies, and found that the velocity dispersions as a function of radius are consistent with a constant Q stability parameter (Toomre, 1964). However, these measurements can now be done with much higher accuracy and much better resolution with the currently available instrumentation.

In all these cases, however, a detailed study of the outer parts of the galaxies has been beyond the scope of the articles, whereas I suggest to focus on these regions, which are of extreme interest if we wish to study the (local) stability of spiral galaxy disks.

2.5 Bulges versus bars in spiral galaxies

The sample of highly-inclined disk galaxies presented in this Thesis could very well be used for the study of the shapes of bulges in different passbands. Since this sample is statistically complete, it can serve to study the occurrence of boxy and peanut-shaped bulges.

Near-infrared observations of highly-inclined disk galaxies could reveal the existence of boxy or peanut-shaped bulges, in the case of heavily obscured galaxies (e.g., Quillen et al., 1997). Therefore, a multicolour study of the central regions of edge-on galaxies will be useful to study these features.

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