Edge-on disk galaxies

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Chapter 1 | *The three-dimensional light distribution in disk galaxies*

Abstract. This introductory chapter contains an overview of the current status of research in the field of galaxy formation and evolution, in which detailed statistical observations of edge-on galaxies can provide better insights. First, the main observational and theoretical questions are summarized. Then follows a discussion on the use of vertical luminosity distributions, vertical and radial colour gradients, and stellar warps as a function of wavelength as diagnostic tools to study the ongoing evolution of galaxy disks. At the end of this chapter an outline of the current thesis work is given.

1 Introduction

A statistical study of the properties of highly-inclined, or 'edge-on' galaxies benefits greatly from the special orientation with respect to the line of sight of such galaxies. Observations of edge-on galaxies provide us with direct measurements of the luminosity distribution both perpendicular to the galaxy plane and along the galaxy's major axis at various heights above the plane. Indirectly, this luminosity distribution can be related to the galaxy's density distribution. Detailed observations of a statistically complete sample of edge-on disk galaxies can provide better insights in several aspects of galaxy formation theory.

In particular, observations of edge-on galaxies in near-infrared passbands enable us to study the galaxy properties, e.g., the vertical luminosity and mass profiles, radial and vertical colour gradients, and the absolute magnitude – colour relation, without being hampered by a contaminating dust influence or any unknown radial dependences.

Moreover, because of the line-of-sight integration through the galaxy disks, in edge-on galaxies one can follow the light distributions further out than for less highly-inclined galaxies and thus one can more easily study the occurrence of stellar warps, as well as their colour dependence.

In this Thesis I will analyse observations of a statistically complete sample of edge-on disk galaxies, obtained in the optical and near-infrared. The conclusions of this Thesis, and those presented in the individual Chapters, are therefore based on statistical considerations rather than on individual cases.

This introductory chapter is meant to give an overview of the *status quo* of the study of edge-on galaxies in optical and near-infrared passbands. Other than a few large edge-on disk galaxies that have been studied individually, they have not attracted much attention until recently. In the following sections, I will discuss the diagnostics that can be used when dealing with edge-on galaxies, as well as the main observational and theoretical questions that yet have to be solved.

In Sect. 2 I start to discuss the information that can be obtained from studying vertical luminosity profiles in various passbands, and compare the observational status with ad hoc and physically more realistic models. In principle, vertical luminosity profiles contain a large amount of information about the disk evolution and the recent star formation history.

Although it seems that warping H I gas layers are extremely common in disk galaxies, the detection of warps in the stellar disks of galaxies has proven to be more difficult. In Sect. 3 I discuss the available evidence for warps in stellar disks, and compare these to the gaseous warps in the context of warp formation theories.

The origins of colours and colour gradients in galaxy disks are discussed in Sect. 4, both along and perpendicular to the galaxies' major axes. The dominant effects that produce colour gradients in highly-inclined or edge-on disk galaxies are caused by dust, however (see, e.g., Chapter 5).

Finally, in Sect. 5 an outline of the current thesis work is given.

2 Vertical disk components

2.1 *The thin disk*

A relatively small number of studies has been devoted to the detailed description of the vertical surface brightness distributions in edge-on disk galaxies. Several models have been proposed and tested to account for the vertical light distributions observed.

2.1.1 The isothermal sheet

Van der Kruit & Searle (1981a,b, 1982a,b; hereafter KS1–4) studied the surface brightness distributions of edge-on disk galaxies in optical passbands. From these studies, they proposed the self-gravitating isothermal sheet (Spitzer, 1942) as a model for the description of the vertical light distribution:

$$L(z) = L_0 \ \mathrm{sech}^2(z/z_0) \qquad (1)$$

where L_0 is the surface luminosity in the plane of the galaxy, z_0 is the vertical scale parameter and z is the distance from the galaxy plane, respectively. At large z heights, the vertical scale heights are equal for both the isothermal model and the exponential approximation, where z_0 equals twice the exponential scale height.

Additional arguments in favour of the isothermal sheet model were provided by Wielen's (1977) analysis of observations of the age-velocity dispersion relation (AVR) of nearby stars. Stars that are older than a few Gyr all have approximately the same velocity dispersion. Thus, as van der Kruit (1988) argued, at least at intermediate z-distances from the Galactic plane, the dominant stellar population has essentially a single velocity dispersion. From numerical calculations of the stellar mix in the solar neighbourhood, van der Kruit (1983) argued that if this component were self-gravitating, the isothermal sheet approximation would be an obvious model.

We can ask whether it is justified to assume self-gravitating processes in disk galaxies to determine the vertical luminosity or density distributions. KS1 argued that the goodness of the fits to the z profiles with the predictions of the locally isothermal sheet suggests that the vertical velocity dispersion of the stars, $\langle v_z^2 \rangle^{1/2}$, is independent of z at a particular radius R. The relations among the values for the central mass density $\rho(0), z_0$, and $\langle v_z^2 \rangle^{1/2}$ for the solar neighbourhood show that the disk of our Galaxy is self-gravitating. The quite similar values for z_0 found by KS1–4 indicate then that it is reasonable to assume that the disks of other galaxies are also self-gravitating.

However, at very low z the thin disk may be not isothermal, due to a mix of the old(er) thin disk stars with younger populations, exhibiting a strong dependence of velocity dispersion on age.

2.1.2 The exponential model

Near-infrared observations of edge-on disk galaxies have shown an excess of light over the isothermal model at small distances from the galaxy planes, where the optical photometry is strongly affected by dust absorption (e.g. Wainscoat et al., 1989; Aoki et al., 1991; van Dokkum et al., 1994, Chapter 3). By supplementing their near-infrared observations with the (partially dust-obscured) optical light distribution, Wainscoat et al. (1989) show that the z-dependence of the light in the large southern edge-on galaxy IC 2531 demonstrates a more strongly peaked profile than expected from the isothermal sheet model, which appears to be better fitted by an exponential law:

$$L(z) = L_0 \exp(-z/h_z), \tag{2}$$

(where h_z is the exponential vertical scale height), although their limited resolution does not unambiguously differentiate between the models. For the vertical K-band light distribution in NGC 891, Aoki et al. (1991) find that the exponential model fits the data remarkably well up to those z-distances where the seeing convolution becomes significant.

Although the exponential model is mathematically attractive because of its simplicity, there is no firm physical basis for such a model. As Burkert & Yoshii (1996) state, an exponential vertical mass density distribution can be constructed by adding up multiple stellar disk components. However, this can only be done if the contributions from stars with larger velocity dispersions are increasingly dominating with increasing distance from the galaxy plane. A mechanism to account for such a process is as yet unknown.

Fuchs & Wielen (1987) tried to fit the results of dynamical evolution models of the Galactic disk to the observed local AVR, in order to calculate both the kinematics and the vertical stellar distribution. They concluded that the resulting vertical stellar distribution was better approximated by an exponential function, whereas the velocity dispersion showed a moderate, but significant gradient with distance from the Galactic plane.

2.1.3 Intermediate solution

However, as van der Kruit (1988) argued, a pure exponential distribution requires a sharp minimum of the velocity dispersion in the plane. Fuchs & Wielen's (1987) results show moderate gradients, much smaller than required for the exponential distribution (Bahcall, 1984a,b). Even when they include all metal abundances in their calculations, the expected gradient is still small close to the plane. Moreover, van der Kruit (1988) also showed that close the galaxy planes the stars are dynamically cooler than expected theoretically from the $\mathrm{sech}^2(z)$ law. Therefore, van der Kruit (1988) proposed that an intermediate distribution, such as the "sech(z)" distribution, could a be more appropriate one to use:

$$L(z) = L_0\ \mathrm{sech}(z/h_z), \tag{3}$$

to account for the deviations from an isothermal sheet in the galaxy planes. Wainscoat et al.'s (1989) near-infrared photometry of IC 2531 would agree with this model, as would star counts for our Galaxy (e.g., Gilmore & Reid, 1983; see also Sect. 2.2).

2.1.4 Isothermal versus exponential distributions

Burkert & Yoshii (1996) find, from realistic hydrodynamical calculations of disk evolution processes, that – if one starts from a non-equilibrium gaseous state – the final vertical stellar density profile depends strongly on the initial distribution of the protodisk gas.

On the other hand, if they assume that the gas settles into isothermal equilibrium prior to star formation and gas cooling, then always an exponential density profile is formed, although the vertical scale height increases as a function of decreasing surface brightness. In fact, de Grijs & Peletier (1997, Chapter 7) present the results of a detailed study of the vertical scale height distributions in a statistically complete sample, for which we found an increasing scale height with galactocentric distance, in particular for the earlier-type galaxies.

An interesting result from the numerical modeling of Burkert & Yoshii (1996) is that when the ratio of the star-formation time scale to the cooling time scale lies in the range between ~ 0.3 and 3, the vertical stellar density distribution becomes exponential, independent of the free parameters in their modeling and also independent of the initial (isothermal) disk temperature and the initial surface density. Therefore, the process of crucial importance is that the SFR is adjusted sooner or later to balance with the local cooling rate (Burkert & Yoshii, 1996).

2.1.5 A multi-component model

However, as Dove & Thronson (1993) warn, if the vertical distribution of stars cannot be fit well by the isothermal sheet approximation, which model is based on physical principles, then rather than invoking an arbitrary alternative function, a more physical function should be that of a nonisothermal stellar distribution, which can be either a distribution of stars that have been formed as a function of time and have not yet settled to an equilibrium state, or a stellar distribution that has undergone dynamical heating during its life time. Oort (1932) already realized that a nonisothermal distribution of stars can be represented by a linear combination of isothermal components. Dove & Thronson (1993) argue that it is possible that once a coeval population of stars has been formed, they do not (or only over a long period of time) interact with other components and are therefore quasi-independent isothermal components. Such a model would be physically realistic, since if stars have formed at different times with different velocity dispersions and have not yet reached an equilibrium state, or if the stars are dynamically heated during their evolution, the resulting distribution of stars would not be well approximated by a single isothermal model.

In fact, the additional velocity components are thought to contain much information about the evolutionary history and physical conditions of the stellar disk. Star formation is generally believed to be a continuous process. Therefore, a more accurate model for a galaxy disk is a superposition of a very large number of components, or, as Kuijken (1991) proposed, an integral representation.

Historically, it has been attempted to classify stellar populations by their position in the colour-magnitude diagram, their differences being mainly due to age and metallicity effects. However, although the terms "Population I" and "Population II" have been in use ever since Baade (1944a,b) originally used them, they are outdated nowadays (see, e.g., King, 1995). Therefore, in this Thesis I will not use them, but instead refer to "old" and "young" disk populations (as opposed to the halo population).

2.2 The Galaxy

Studies of the Galaxy provide valuable information on the vertical structure of galaxy disks. These studies, based on star counts, have the advantage over the studies of external galaxies that they are less affected by dust absorption and effects caused by the presence of a young stellar population. Gilmore & Reid (1983) and Pritchet (1983) conclude that the stellar z-distribution in our Galaxy is better approximated by an exponential than an isothermal profile.

Gilmore & Reid (1983), in deriving the vertical stellar density distribution towards the South Galactic Pole, exclude all stars with $V \geq 18.5$ mag, all K stars with $V \leq 14$ mag and all distances smaller than 100 pc or larger than 1000 pc from the Galactic plane. The 100 pc lower distance limit arises both because they have very few stars nearer than this and because of possible contamination by young disk stars. The 1 kpc upper limit is the distance beyond which the single exponential fit is no longer valid. Their final result is that for $z \leq 1.0$ kpc the data are very well fit by a single exponential with a scale height $\sim$ 100 pc for stars with absolute V-band magnitude $M_V \leq +4$ and $\sim$ 300 pc for fainter stars.

On the other hand, Hill et al. (1979) derived density laws for A and F dwarfs towards the North Galactic Pole, which cannot be fit well by an exponential distribution, although they may be approximated as such in short distance bins. They find that the F stars are roughly consistent with a single exponential; the A stars, however, can only be approximated by a single exponential closer to the Galactic Plane and with a significantly smaller scale height than the F dwarfs.

Based on observations in the near-infrared, Kent et al. (1991) concluded that the vertical light distribution (and hence probably also the mass distribution) in the Galaxy follows an exponential law more closely than an isothermal sheet model. However, they did not compare the observed light profiles to other model distributions.

From recent work (e.g., Haywood et al., 1997a,b) it appears that the single exponential vertical density distribution does not well explain the multi-wavelength observations and star counts of the Galaxy's large-scale structure. Haywood et al. (1997b) conclude that the vertical density distribution of disk stars towards the North Galactic Pole decreases much faster than the conventional single exponential distribution, and that single-valued exponentials do not describe the star-count data accurately. These results are, in fact, consistent with those published previously.

2.3 The vertical scale height

KS1–4 found, at least for their sample of edge-on spirals, that the vertical scale height is in good approximation independent of position along the major axis. Later studies of NGC 891 (Kylafis & Bahcall, 1987), NGC 4565 (Jensen & Thuan, 1982), and NGC 5907 (Barnaby & Thronson Jr., 1992) have confirmed this result. Shaw & Gilmore (1990) studied a sample of 10 spiral and lenticular edge-on galaxies for which they found, from two-dimensional modeling, that the variation of disk scale heights as a function of radius is typically within $\pm$ 3% of the derived mean value, with no evidence of a dependence on colour or model type adopted. In some of their sample galaxies they concluded that the best-fitting model is a combination of two disk components, a thin and a thick disk. The scale height was found to be constant at the same 3% level in both disk components.

A possible explanation (KS4; Barnaby & Thronson Jr., 1992) for the constancy of the scale height is that it is the result of secular evolution of a galaxy if:

- The disk is continuously heated by a mechanism such as that originally proposed by Spitzer & Schwarzschild (1951), namely the random acceleration of the disk stars by giant molecular clouds or spiral structure (see also Lacey, 1984; Carlberg & Sellwood, 1985). This mechanism increases the speed of the stars and leads to the distribution of vertical velocity dispersion observed in disk stars in the Galaxy and external galaxies.
- At all times the star formation rate (SFR) is proportional to the surface number density of the giant molecular clouds, so that roughly the same proportion of stars will form per unit mass of molecular clouds at all radii.

The result of these constraints is that the radial distribution of both the vertical velocity dispersion and the surface mass density of the luminous matter is determined by the radial distribution of the giant molecular clouds. Since the vertical velocity dispersion and surface mass density possess similar radial distributions, their ratio has no radial dependence. KS1 and van der Kruit (1988) showed for the isothermal disk case that the scale height is proportional to this ratio. Thus, the scale height will also not exhibit a dependence on radial distance.

However, to date there is no satisfactory explanation as to how disk heating, the rate of which must vary greatly with radius from the observed distribution of molecular clouds in our own and other galaxies, can naturally lead to this result (see also de Grijs et al., 1997 [Chapter 8]).

An alternative explanation for the constancy of the scale height was proposed by Bertin & Lin (1987), who invoked the so-called "self regulation" mechanism for galaxy disks, which presumably causes the spiral structures observed in external galaxies. They assume that young "cold" stars are born in a dynamically cold gas layer in the disk of a galaxy. These young stars will cool the stellar disk, which causes a spiral instability to arise. This, in turn, causes the heating up of the disk. The spiral arms will then form new stars, which will cool the disk again, in this way establishing a stable situation in the disk. This leads to a more or less constant value for Toomre's (1964) Q parameter as a function of radius. Combined with an exponentially decreasing velocity dispersion as found in exponential disks this leads to a constant scale height (Bottema, 1993).

However, on closer inspection the constancy of the scale height seems to lose strength in the (radially) outer parts in a number of galaxies (see, e.g., de Grijs & Peletier, 1997 [Chapter 7]). For our Galaxy, Kent et al. (1991) find indications that the scale height increases linearly with radius from a minimum radius outwards. The outermost profiles of NGC 4244, NGC 5907 (KS1), and NGC 891 (KS2) do seem to indicate smaller slopes. Quinn et al. (1993) find, from numerical simulations, that disks following accretions are noticeably flared. The projected and deprojected scale heights of both the original disk and of the final system increase with radius. The improvement over models with a fixed scale height is significant, although not dramatic. It is therefore possible that the disk thickens just before the (radial) cutoff (KS1). Another possibility is that optical warps are present, like in the HI, causing the shallower outer profiles. However, even if the shallowing at the outermost vertical luminosity profiles were entirely due to a thickening of the disk, the implied change in z_0 would be relatively small and restricted to no more than 10% of the observable extent of the galaxies (KS1).

2.4 The thick disk

Another vertical luminosity component in disk galaxies was first detected by Burstein (1979) in a small sample of edge-on S0 galaxies. This component is referred to as the "thick disk", because it has a larger scale height than that of the dominant disk component. To be clearly distinguishable from the main disk component, thick disks are characterized as follows (Burstein, 1979):

- The thick disk has an intrinsic ratio of total z-thickness to diameter, z/a, of between 1/4 to 1/5 at $\mu_B \sim 25$ mag arcsec^{-2}, whereas an E4 elliptical has $z/a = 0.6$ and a thin disk $z/a \leq 0.1$;
- The surface brightness of the thick disk *parallel* to the major axis decreases very slowly with increasing galactocentric radius, in marked contrast to the radial luminosity gradients of bulges and thin disks;
- The thick disk also does not appear to be as sharply peaked as a bulge or a thin disk perpendicular to the major axes. In this sense it may be characterized as being the most "diffuse-appearing" of the three luminosity components (including the bulge, the thin and the thick disks).

Although the presence of a thick disk component in our Galaxy is generally accepted (having a scale height of ~ 1 kpc), in external galaxies, the existence of thick disks has not been proven unambiguously. Probably one of the most convincing examples of the existence of a thick disk component was found by van Dokkum et al. (1994, Chapter 3) in the case of the edge-on spiral NGC 6504, with a scale height of approximately 4 times the thin-disk scale height.

A number of possible origins for these thick disks can be thought of. They could be truly separate dynamical components of the galaxies, or due to the bulge light contribution (Freeman, 1985). The thick disk, according to KS2, Freeman (1985) and Bahcall & Kylafis (1985), could be the spheroidal component itself, responding to the flat potential of the disk (Jarvis & Freeman, 1985) or it could be an intermediate population that formed as the spheroid formed (e.g., Gilmore, 1984).

However, de Grijs & Peletier (1997, Chapter 7) argue that it is likely that the formation mechanism for the thick disk and the origin of the increasing scale height as a function of projected galactocentric distance are similar. It seems therefore natural to link this increase of scale height with radius to the presence of a thick disk. The possibility that the thick disk is the intermediate component in the hierarchical formation scenario between the bulge and the thin disk seems to be ruled out by the large scale length of the thick disk. Therefore, more likely formation mechanisms for the thick disk invoke the accretion of material by the early thin disk, causing violent dynamical heating processes to take place, thereby puffing up the thin disk (e.g., Norris, 1987; Statler, 1989; Quinn et al., 1993).

3 Stellar warps in galaxy disks

3.1 Introduction

Many galaxies, including our own, show large-amplitude warps in the outer parts of their disks, although the degree and large-scale symmetry of the warping vary substantially among galaxies. Usually, warps are much more pronounced in HI observations than in the optical (e.g., Briggs, 1990; Binney, 1992), because they often begin at those galactocentric distances where the optical disks are faint.

Warps are most clearly visible in external galaxies that are seen edge-on, although from galaxies that are seen more face-on, the existence of warps can be inferred from abnormalities in the velocity field over the disk, as – for instance – in the cases of M31 (e.g., Innanen et al., 1982, and references therein), M33 (Rogstad et al., 1976) and M83 (Rogstad et al., 1974).

Although warps seem to be a gaseous feature of disk galaxies, stellar disks tend to follow the HI warps at their outer edges. Sánchez-Saavedra et al. (1990) claim that in almost half of the edge-on galaxies on northern sky survey plates some sort of warping feature is observed. Battaner (1995) argues that existing observations of southern edge-on galaxies support this claim. Both Sasaki (1987) and Morrison et al. (1994) argue that the observation of a warping feature in NGC 5907 in a number of optical and near-infrared passbands implies that these warps are not merely gaseous, but also intrinsic to the *stellar* disks themselves.

Since optical warps can only be detected if the line of nodes (i.e., the intersection points with the galaxy plane of concentric rings in a tilted-ring model) of the stellar warp lies relatively close to the direction perpendicular to line of sight, this implies that virtually all disk galaxies must be warped (e.g., Briggs, 1990). However, Bottema (1996) cautions that a corrugated dust lane can mimic the presence of an optical warp. Nevertheless, in many edge-on galaxies warps are detected unambiguously in optical passbands.

Based on HI observations of a small sample of warping galaxies, Briggs (1990) concluded that the warp proper develops between the radius at which the B-band surface brightness equals $\mu_B = 25$ mag arcsec^{-2}, and the Holmberg radius, $R_{\rm Ho}$, at which $\mu_B = 26.5$ mag arcsec^{-2}. In general, within $R_{\rm Ho}$ the line of nodes is straight, whereas it tends to form a loosely wound spiral at larger radii.

Since warps are so common, it has been suggested that, once present, they persist for a long time (e.g., Hunter & Toomre, 1969, hereafter HT69; Sparke & Casertano, 1988, hereafter SC88). However, the bending of the galaxy disks is observed at radii where a free particle precesses quite rapidly in the gravitational field of the disk. Therefore, solutions have been proposed to sustain the warping structures observed, like the continuous renewal of the warp, a considerably delayed destruction mechanism, or a stabilisation mechanism, see Sect. 3.3.

3.2 The Galactic warp

Many studies have been devoted to the warp in our own Galaxy. For instance, the most distant HI does not conform to the Galactic plane at all longitudes. Around $\ell = 90°$ the distant gas is located north of the plane, whereas near $\ell = 270°$ it is below the plane (Burton, 1988; Gilmore et al., 1989).

The Galactic HI warp starts at about 12 kpc from the Galactic centre and seems to grow linearly and approximately equally in both the northern and the southern Galactic hemispheres, until about $R = 16$ kpc. At larger radii, the warp amplitude in the northern hemisphere continues to increase, whereas the southern-hemisphere gas layer returns towards the Galactic plane after having reached a maximum amplitude of $\sim$1 kpc below the plane at $R \sim 18$ kpc (e.g., Burton, 1988).

Although the Galactic warp starts at $R \sim 12$ kpc, at which radius freely rotating particles would rotate twice as rapidly around the Galactic centre as test particles near the outer edge, the line of nodes of the Galactic warp is approximately constant (Burton, 1988). It thus seems that precession due to differential Galactic rotation is somehow counteracted by an as yet unknown physical mechanism.

It is also unknown whether the Galactic stellar disk follows the HI warp. Optical studies of the young disk tracers are often severely hampered by the interstellar extinction and by incompleteness effects.

A number of studies have dealt with the optical counterpart of the HI warp in the Galaxy (e.g., Djorgovski & Sosin, 1989, and references therein; Porcel & Battaner, 1995). The optical tracers used in most of these studies are young, with ages generally smaller than a Galactic rotation period, and could therefore have formed in the warp itself, near their present locations. For that reason one cannot draw firm conclusions on the warp's longevity and persistence from the distribution of its young optical tracers.

Djorgovski & Sosin (1989) concluded, based on the *IRAS* observations, that the old stellar population, represented by AGB or post-AGB stars with dust shells, follows the HI warp, although not exactly. The amplitude of the *IRAS* warp is several times smaller than that of the HI warp. This means that the Galactic warp is a feature of the Galaxy as a whole and not just of the gaseous component (Djorgovski & Sosin, 1989).

The observation that the Galactic warp is traced by a relatively old, evolved stellar population implies that it is a long-lived phenomenon, since the life times of AGB stars in the range of IRAS luminosities observed are on the order of a few times 10^9 years (Aaronson & Mould, 1985).

Although the warp traced by the evolved stellar population does not trace the HI warp exactly, it seems that the optical warp defined by the (young) OB associations is equal or even stronger than the gaseous warp. Porcel & Battaner (1995) interpret this observation as a result of Galactic extinction, since low-Galactic latitude stars are discriminated against in the selection of distant young tracers.

We will discuss the wavelength dependence of the observed warp curves in more detail in Sect. 3.3.1.

Ever since the detection of the Galactic warp in HI, it has been suggested that the Magellanic Clouds have caused the gaseous distortion by their gravitational pull, although it was doubted that the Clouds could be sufficiently massive to account for the observed warping (e.g., Burke, 1957; Kerr, 1957). HT69 considered the possibility that the warped Galactic gas layer was pulled out of its plane by a single close passage of the Large Magellanic Cloud. Their conclusion was, however, that a warp amplitude caused by such an encounter falls short by a factor of about 3 compared to the observed warp amplitude.

In the next section, we will consider various formation mechanisms for galaxy warps and their ability to sustain a warping feature for up to a Hubble time.

3.3 The formation and persistence of gaseous and stellar warps

Various formation mechanisms have been proposed to account for the warps seen in the majority of disk galaxies. A warp could be excited by

- an external force, like the tidal interaction with nearby galaxies (e.g., HT69), the pressure of the intergalactic gas (Kahn & Woltjer, 1959), or the influence of extragalactic magnetic fields (Battaner et al., 1990);
- an internal force due to instability in a stellar and/or gaseous disk (e.g., Binney, 1978; 1981) or due to a (discrete) bending mode in the disk (e.g., HT69; SC88);
- a primeval origin such as free precession of the disk (Lynden-Bell, 1965), the formation of an inclined disk or halo (e.g., Dekel & Shlosman, 1983; Tubbs & Sanders, 1979), or the infall of extragalactic material, like HI clouds (e.g., Saar, 1979; Gunn, 1982) or gas-rich dwarf galaxies (Bottema, 1995).

3.3.1 Comparison between stellar and gaseous warps

If warps are gravity-induced, the stellar and gaseous warps should behave similarly, because gravity affects stars and gas in the same way. However, if warps are caused by magnetic fields or intergalactic gas pressure, the gas layer should respond more strongly to the forces exerted upon the disk than the stellar component. Therefore, ideally one would compare observations done in different optical passbands, representative of various stellar populations, as well as HI observations, which trace the gas component. Such a comparison can help distinguish between the possible formation mechanisms.

In a number of warping edge-on galaxies, for which observations with high spatial resolution of the outer parts are available, it is found that, although the stellar warps generally follow the HI warps in the same direction, the spatial differences are appreciable (e.g., Jensen & Thuan, 1982; Sasaki, 1987; Florido et al., 1991).

Although the HI layer exhibits a larger warp, Sasaki (1987) observed in NGC 5907 a spatial coincidence of the warp in the optical F and J passbands. On the other hand, Florido et al. (1991) found, in a number of highly-inclined disk galaxies, a clear wavelength dependence also between optical passbands, in the sense that the bluest colours (representing the youngest stellar populations) showed the largest deviations from the galaxy planes, similar to the observations of the Galactic warp (see Sect. 3.2).

Florido et al. (1991) argue that these differences cannot be caused by extinction, as was suggested by Sasaki (1987), since extinction will reduce the actual separation between warps observed in the gaseous component, the young and the old stellar populations. Therefore, intrinsic colour gradients will be reduced rather than emphasized by extinction effects.

Alternatively, if warps are excited by a discrete bending mode in a sharply truncated galaxy disk (e.g., HT69; SC88) it can be expected that the warp curves determined from the gas layer and younger stars (that will have formed recently from the interstellar gas), will be slightly offset from warp curves based on emission from the older stellar populations, due to the greater gaseous viscosity.

The discrepancy between the observed spatial positions of the stellar and gaseous warps can be explained by invoking projection effects rather than a physical separation between the stars and the gas layer. Because of the sharp truncation of the stellar disk observed in a number of edge-on galaxies (e.g., KS1–4), the stellar warp appears weaker than the HI warp (e.g., Sasaki, 1987, based on a tilted-ring model with a sharp truncation for NGC 5907). Freudenreich et al. (1994) also advocated projection effects to explain the differences between the Galactic warp observed in the near-infrared and that in HI gas.

Porcel et al. (1997) support this hypothesis by pointing out that the observed warp curve, based on the *DIRBE* experiment flown on board *COBE*, argues in favour of a cut-off of the Galactic stellar disk at about $R = 15$ kpc. This truncation radius is in agreement with that found by Ruphy et al. (1996), based on *DENIS* observations. However, Porcel (1997) reaches the opposite conclusion in his Ph.D. Thesis, based on the same observations.

Such a projection effect can occur if the direction of the maximum vertical displacement of the stellar disk differs from the line of nodes and if the stellar disk is much smaller than the gaseous one. Cox et al. (1996) reported that for NGC 7170 they did not find any evidence for a spatial separation between the optical and HI warps. In view of the absence of a sharp truncation of the stellar disk and because the HI gas extends only slightly further out than the stellar disk, it is indeed expected that these projection effects do not occur.

The stellar and gaseous warps thus seem to be very similar.

3.3.2 Gravitational interaction

To explain the origin of the Galactic warp, HT69 and others investigated the possibility of a recent tidal interaction or close-by encounter with the Magellanic Clouds (see also Sect. 3.2). However, although the tidal interaction theory may be attractive to explain the warps in individual cases (e.g., Jensen & Thuan, 1982 [NGC 4565]; Bottema et al., 1987 [NGC 4013]; Sasaki, 1987 [NGC 5907]) strong warps have also been observed in many isolated field galaxies (e.g., Sancisi, 1976; Cox et al., 1996).

Bottema (1995) argues that the fact that the HI warp in NGC 4013 abruptly starts at the edge of the stellar disk is in agreement with the gravitational interaction hypothesis: if the matter density is also truncated at the edge of the stellar disk, a gravitational disturbance can easily cause the warping feature beyond the truncation radius, whereas self-gravity counteracts the effects of an external disturbance in the stellar disk. It is – in this context – also possible that an external disturbance has pulled the gas out of the disk everywhere, but if so, it is likely that the gas that was torn out of the stellar disk will have settled back in the galaxy plane quickly again by dissipational and dynamical friction inside the truncation radius (Bottema, 1995). Other galaxies, like NGC 4565 and NGC 5907, also show a sudden strong HI warp that starts at the edge of the stellar disk (Sancisi, 1983).

However, HT69 have shown that for any reasonable flattened galaxy, differential precession will cause both a stellar and a gaseous warp to damp out within a few galactic rotation periods. However, to obtain the high degree of symmetry observed in many warping galaxies, several rotation periods are needed. Tubbs & Sanders (1979) showed that warps can be sustained considerably longer, up to 10^{10} yr, in the presence of a spherically symmetric gravitational field, which can be provided by, for instance, a spheroidal halo, which is at least three times more massive than the disk. The disk itself should be finite, so that it will not destroy the spheroidal gravitational field at the warp's position. Clearly, the sharply truncated stellar disks fulfill these requirements.

Moreover, Burton (1988) remarks that the symmetry and regularity of warped galaxies, and of our own Galaxy in particular, seem to argue against the tidal interaction hypothesis. As Byrd (1978) showed, tidal interactions of M32 with M31 would only disturb a small portion of either galaxy rather than produce a global distortion.

3.3.3 Infall of extragalactic material

Kahn & Woltjer (1959) first suggested that the gaseous disk component in the Galaxy is pulled out of its plane by external forces exerted upon it by a flow of intergalactic gas around the halo and the resulting redistribution of angular momentum in the halo. Bottema (1995) revisited this idea and proposed that a continuous infall of gas-rich dwarf galaxies in the halo can periodically renew the outer warp.

In the context of the Cold Dark Matter cosmogony galaxies formed by accretion and mergers of smaller lumps of matter (e.g., Ostriker & Binney, 1989). It is therefore expected that this process of "secondary infall" in the outer galactic haloes is still ongoing. Although Tóth & Ostriker (1992) have put strict upper limits to the number of accreted big lumps per Hubble time, an unlimited number of sizeable lumps can have flown by the galaxy without having been subjected to sufficient gravitational pull to spiral in. Binney (1992) suggested that thin disks may exhibit their observed sharp truncations precisely because at larger galactocentric distances a stellar disk cannot be maintained due to the large number of extragalactic lumps that tend to distort the disk at those radii.

However, as Bottema (1996) pointed out, this process can only explain one-sided warps (like in NGC 4565) or otherwise irregular warps. It takes a few galactic rotation periods for a gas cloud that has been accreted to regularize into a symmetric structure. On the other hand, differential precession tends to wind up the warp on a similar time scale, so some kind of stabilising mechanism is needed to explain the persistence of the observed warps.

3.3.4 Intergalactic magnetic fields

As in our Galaxy, the warp curves in a few external edge-on galaxies also show a wavelength dependence, in the sense that at shorter wavelengths the separation between the HI warp and the stellar warp is smaller than at longer wavelengths (e.g., Florido et al., 1991).

If gravity were the prime cause for the warping structures, the distortion of stars and gas would be expected to be identical. Although gas and stars do not necessarily respond to gravity in the same way, under the influence of external gravitational forces no difference in the warps defined by the young and old stellar populations would be expected.

However, if the warp is induced by an external force to which the stars respond differently than the gas, a deviation between the stellar and gaseous warps is foreseen. Intergalactic magnetic fields, for instance, would primarily act on the gaseous galaxy components, so that any warp resulting from external magnetic forces will be at first a gaseous distortion. A stellar warp would follow due to subsequent star formation in the gaseous warp. However, although the young stars will trace the gaseous warp closely, the older stars would have had time to return to the original galaxy plane, or to disperse their warped distribution (Florido et al., 1991). Therefore, the analysis of colour gradients in the warp may lead to a better understanding of its origin (see also Chapter 9).

Battaner et al. (1990, 1991) argued that intergalactic magnetic fields of order 10^{-6} to 10^{-8} G can produce warps in the gaseous disks of galaxies and that a uniform intergalactic magnetic field can actually explain the observed warps within about 20 Mpc of the Galaxy, including the warps of the Galaxy, M31 and M33. Although Binney (1991) rejects this mechanism, arguing that implausibly high field strengths are required to account for the observed warps, Battaner (1995 and priv. comm.) points out that very large intergalactic magnetic fields on the order of the required 1–3 μG seem to be ubiquitous (e.g., Kronberg, 1994).

However, as was discussed in Sect. 3.3.1, the apparent separation between the stellar and the gaseous warp curves does not need to be real, but can be caused by the relatively abrupt truncation of the stellar disk embedded in a more extended HI gas disk.

3.3.5 Disk bending modes

Originally, Lynden-Bell (1965) proposed that warped galactic disks might represent discrete bending modes under the influence of their own gravity. This idea was elaborated upon by, e.g., HT69, who concluded that only in disks with sharp outer edges normal modes occur at discrete frequences, implying that warps might be sustained for a Hubble time without being distorted by differential precession. A disk that is subjected to a discrete warping mode will settle from the inside out, giving rise to a straight line of nodes (HT69; SC88). Cox et al. (1996) have shown that the settling time is of order a Gyr.

However, as HT69 already remarked, if the disk mass is not sharply truncated, the warp will exhibit a continuum of bending modes and cannot be maintained sufficiently long because of differential precession. If a disk which shows a continuum of bending modes is somehow forced to warp, the outer regions will warp strongly, because the only way to dissipate the energy carried outwards by the bending waves is by the vertical heating of the disk. Then, this outer strongly warped region will rapidly dissipate its energy and hence the warp will be dissolved quickly (SC88). If the outer edge is sufficiently sharp, however, the bending wave can be reflected and a stable warp may form.

If the disk is embedded in a dark halo, however, the warp may be sustained longer, since discrete bending modes will arise, in particular if the halo is somewhat flattened (e.g., SC88). This behaviour does not depend on exactly how the disk is truncated, provided that the truncation region is not too extended.

Hofner & Sparke (1994) have shown that a warp characterized by a discrete bending mode in a self-gravitating disk subject to a fixed potential of a flattened dark halo will settle to this mode, with a straight line of nodes in the inner, settled disk, and will eventually develop a leading spiral form in the outer parts. They argue that this is in agreement with the results of Briggs (1990), which imply that in the outer regions of the galaxy the disk has not yet completely settled in the potential of the dark halo.

3.3.6 The effects of a dark halo and self-gravity

Effects due to the gravitational potential of the dark halo can be invoked to both give rise to and maintain the observed warps. Djorgovski & Sosin (1989) argued that a triaxial or oblate dark halo, misaligned with a galaxy disk, could cause the warping (e.g., Dekel & Schlosman, 1983; SC88). It has been shown that haloes need not be triaxial, but oblate haloes are sufficient or even preferable (SC88).

Binney (1992) argued that the central mass density of the combined disk-halo system will be strongly influenced by the disk, so that an inclined (rigid) halo potential cannot be maintained. From numerical calculations Dubinski & Kuijken (1994) and Nelson & Tremaine (1995) concluded that the halo becomes rapidly aligned with the disk and, as a consequence, the warp is dissolved.

As Bottema et al. (1987) argued, a large warp cannot be sustained in a disk-like gravitational potential alone for more than a few galactic rotation periods; if a spherical or halo potential is added, it will persist substantially longer. They supported this argument by pointing out that at the truncation radius of the stellar disk of NGC 4013 both the HI warp rises abruptly and the rotational velocity suddenly drops, so at this radius a change from a disk-like to a more spherical potential is likely. In the halo dynamical friction is important, which thus delays the settling of the warped gas layer in the galaxy plane (e.g., Dubinski & Kuijken, 1995).

In this context, it was argued that haloes with large core radii or high densities are needed to be sufficiently effective in sustaining a warped galaxy disk (e.g., SC88; Hofner & Sparke, 1994; Dubinski & Kuijken, 1995). The observation that HI warps appear more often in galaxies with large (halo) core radii (Bosma, 1990, 1991) argues in favour of this hypothesis.

Finally, although the presence of a dark halo may slow down the precession of free particles at different galactocentric distances in the warp region, this delayed winding up with time will be much more effective if we assume the galaxy disks to be self-gravitating (e.g., May & James, 1984; Hofner & Sparke, 1994). If a warp exists only in low-density HI gas outside the stellar disk, its self-gravity can probably be neglected. On the other hand, if the stellar disk, or a relatively dense HI disk exhibits warping, its self-gravity cannot be neglected anymore. Torques due to self-gravity tend to modify the precession rate until the warped disk has settled to the bending mode shape; from that moment it will precess rigidly (Hofner & Sparke, 1994).

3.3.7 Concluding remarks

To date, a physically realistic mechanism to account for both the formation and the persistence of warps in disk galaxies, either stellar or gaseous, has not yet been found. All of the mechanisms postulated suffer from incompleteness or the inability to explain the warping stellar and gaseous features in detail. However, due to the large number of unknown variables, the solution of this problem is not straightforward. Binney (1992) pointed out that, due to the complexity of the physical processes involved, in calculations one often simplifies reality and thus one introduces large uncertainties. The following simplifying assumption are often made:

- The neglect of non-gravitational forces. Warps may respond differently to pressures exerted by the intergalactic matter (e.g., hydrodynamical (gas) pressure or pressure due to magnetic fields) than to gravitational forces. Moreover, the response of the stellar and gaseous components to these kinds of pressure will be different.
- The shape of the dark matter halo: is it spherical or oblate; axisymmetric or triaxial? Is the line of nodes somehow aligned with one of the halo's principal axes?
- The gravitational potential of the galaxy disk. Generally, it is assumed that the disk potential is fixed. However, a distortion of the disk into a warped configuration will modify the disk potential, and therefore self-gravity has to be taken into account.
- The halo's gravitational potential. Although one often assumes that the halo potential is unresponsive, it must somehow respond to changes in the disk potential if a warp is formed. It appears that the outer haloes of many galaxies must be torquing the inner galaxy-halo combination (e.g., Quinn & Zurek, 1988).
- Galaxies are usually modeled as isolated entities; in reality, however, it is likely that they accrete extragalactic material or are subjected to gravitational forces arising from close encounters with other galaxies.

4 Disk colours and colour gradients in edge-on galaxies

4.1 Galaxy structure inferred from colour profiles

In contrast to the large number of studies of radial colour gradients in moderately inclined and face-on spiral galaxies (e.g., de Jong, 1996b, and references therein), the colour behaviour of highly inclined and edge-on galaxies has not received much attention. In highly inclined galaxies, the interpretation of intrinsic colours and colour gradients is severely hampered by the presence of dust in the galaxy planes, which causes the dust lane to appear as a red feature in vertical colour profiles (e.g., Hamabe et al., 1979, 1980; KS3,4; Sasaki, 1987; Wainscoat et al., 1989; Aoki et al., 1991; Jansen et al., 1994).

If the dust lane is resolved, the presence of HII regions and a young, blue population of O and B stars very close to the galaxy plane can be inferred from the vertical colour profiles. As was noted by, e.g., KS3 for NGC 5907 and Wainscoat et al. (1989) for the southern edge-on IC 2531, the relative prominence of the young disk in the bluer passbands, where reddening plays an increasingly important role, means that the young disk is very blue compared to the dominant disk component. The blue stars of which the light is observed must be located at sufficiently large radii, in order to compensate for dust absorption.

In our Galaxy the young stellar population also resides in a thin disk with a much smaller scale height than that of the old-disk stars (e.g., Bahcall & Soneira, 1980). The major contribution to the luminosity of this population comes from the young, massive stars, which results in a blue appearance.

4.2 Observational evidence

It is well-known that the colour gradients seen in moderately inclined and face-on galaxies indicate bluer colours with increasing galactocentric distance (e.g., de Jong, 1996b, and references therein). However, only for a few (relatively large) edge-on galaxies colour data are available and colour gradients have been measured.

4.2.1 Major axis colours

In edge-on disk galaxies it is generally found that the colours along the galaxies' major axes, i.e., the locations of the dust lanes, remain nearly constant (e.g., Sasaki, 1987; Wainscoat et al., 1990; Aoki et al., 1991), although in most cases the outermost disk regions tend to be slightly bluer on the major axis (e.g., Sasaki, 1987). This increasingly blue light could be explained in terms of an increasingly metal-poor population or a decreased amount of dust at larger galactocentric distances. The near constancy of the dust lane colour with position along the major axis in NGC 4594 and NGC 7814 led Wainscoat et al. (1990) to the conclusion that this is more consistent with a ring rather than with an exponential disk of dust, which would produce a gradually redder colour towards the nucleus.

4.2.2 Colour profiles parallel to the major axis

Jensen & Thuan (1982) found a colour gradient along the major axis of NGC 4565, which becomes statistically insignificant as the height above the dust lane and its embedded young disk increases. They argue that this is consistent with Schweizer's (1976) conclusion, that the old-disk populations of Sb and Sc galaxies are very uniform in colour. These results have been confirmed for a number of edge-on galaxies by Hamabe et al. (1979, 1980) and KS3,4, although a slightly decreasing colour index may also be possible, in particular for NGC 891.

KS3 showed that the disk colours in NGC 5907 are nearly constant over the entire disk at a z height where the influence of the dust lane can be assumed to be negligible. Sasaki (1987) studied NGC 5907 in more detail and found that, at different heights above the galaxy plane, there are trends of an increasingly dominant blue component in the (radially) outermost disk parts. The colour gradient therefore seems to be intrinsic to the disk. Differences between colour profiles extracted parallel to the major axis can be explained by a vertical colour gradient.

4.2.3 Vertical colour profiles

Detailed studies of the colour behaviour of galaxy disks perpendicular to their planes (e.g., Hamabe et al., 1979; Hegyi & Gerber, 1979; KS2; Jensen & Thuan, 1982) are consistent with a small gradient or no colour gradient at all outside the dust lane region (see also de Grijs et al., 1997 [Chapter 8]).

Although colour gradients found along the minor axis may be due to some intrinsic bulge property, KS2 observed that, at various galactocentric distances, the vertical colours of NGC 891 are getting systematically bluer with larger height above the plane. On the other hand, Jensen & Thuan (1982) did not find any evidence for a vertical colour gradient in NGC 4565 in the region where the old disk dominates. However, as soon as the light of the thick disk starts to dominate they notice a small perpendicular colour gradient towards the red.

4.3 Colours and colour gradients as diagnostics

Broad-band colours are relatively easy to obtain and are therefore the most widely used colour diagnostics to date. Moreover, they immediately reveal the approximate nature of a galaxy, which is to first order determined by the dominant stellar population and dust content. However, for the detailed analysis of the luminosity and colour profiles of edge-on galaxies one needs to adopt *a priori* assumptions concerning the evolutionary stellar population synthesis, the initial mass function, the metallicity and the star formation history, as well as about the dust geometry and its characteristics. Due to the relative insensitivity of broad-band colours to these characteristics, spectral line studies seem to be a more effective tool to disentangle metallicity and age effects, as well as population gradients.

However, de Jong (1996b) pointed out that the colours formed from different broad-band combinations correlate strongly for his sample of face-on spiral galaxies. Therefore, broad-band colours can be used as indicators of changes in the gross properties of galaxies, in the absence of dust. Different wavelength ranges can be used as diagnostics for different overall galaxy properties.

4.3.1 Ultraviolet–optical colour indices

Strom et al. (1976, 1977, 1978) suggested that the ultraviolet–optical colour index is an efficient tool to investigate the metallicity changes within and among galaxies (e.g., Faber, 1973; Frogel et al., 1978).

The ultraviolet–optical colour index in the old stellar population is expected to be a good measure of the chemical composition within a given galaxy, because (1) it is sensitive to variations of the effective temperature along the giant branch; (2) it gives an indication of the number of blue horizontal branch stars relative to giant branch stars, which is supposed to be a sensitive metallicity indicator (Strom et al., 1977); and (3) it is sensitive to the effects of the metallicity on "blanketing" in U and V, i.e., the fact that stars of a given effective temperature and lower metal abundance contribute mainly in the blue wavelength range.

It is important to note that these colours can trace the chemical composition, assuming that star formation has ceased long ago or only plays a minor role. If the effects of star formation are not negligible, the colour-index change will closely match the metallicity changes induced by the recent star formation history (Strom et al., 1978). However, especially when dealing with (edge-on) disk galaxies, one has to be cautious, as the effects of dust cannot be disentangled easily from population changes (see, e.g., Balcells & Peletier, 1994; Peletier & Balcells, 1997; and others).

4.3.2 Optical–near-infrared colour indices

In a very instructive study of the inner region of M100, Knapen et al. (1995) showed that the I–K colour index is a good tracer of localized dust extinction (whereas the population component is minimized); the U–V index is so for the presence of young stars (Knapen et al., 1995).

In dust-free elliptical and lenticular galaxies, the optical–near-infrared colour index gradually decreases with galactocentric distance (e.g., Strom et al., 1976), implying decreasing metallicity. Unfortunately, in the dustier spiral galaxies, the interpretation of such a colour gradient (or its absence) is less straightforward.

The *intrinsic* B–K and V–K vertical colour gradients in an edge-on disk galaxy should be positive with increasing distance from the galaxy plane, due to the smaller scale height of the youngest (bluest) population compared to the older populations. However, as Skrutskie et al. (1985) pointed out, based on observations of three large edge-on disk galaxies, vertical colour profiles taken at and parallel to the galaxies' minor axes show the opposite trend. They interpret this as due to extinction effects. However, it may also be due to the presence of a thick disk in their sample galaxies.

In general, broad-band colours can be used to study the dust content of galaxies statistically, because the wavelength dependence of dust extinction generates reddening (see, e.g., Chapter 5). Peletier & Balcells (1997) present a detailed colour analysis of a sample of 30 nearby S0 to Sbc galaxies with inclinations larger than 50 degrees. In particular, they present minor axis colour profiles, which allow for the study of bulge and disk colours unaffected by extinction.

4.3.3 Colour gradients from scale length ratios

Since the dust influence varies as a function of passband, scale length ratios could be used as a diagnostic to estimate colour gradients and the dust content of a given galaxy.

Evans (1994) studied the effects of dust on the stellar scale length as a function of wavelength, under the assumption that the resulting scale length differences are solely due to dust absorption. His models predict that these differences are small, at least for face-on galaxies, in the order of the observational uncertainties, and even smaller for galaxies with a prominent bulge component. According to his models, if the scale height ratio between dust and stars is ~ 0.5 (Peletier & Willner, 1992; Evans, 1994), Evans' (1994) models exclude face-on galaxies with $h_B/h_H \approx 2$. On the other hand, larger ratios can be obtained if a galaxy is inclined with respect to the line of sight.

The measurement of blue to red scale length ratios alone will not unambiguously reveal the dust content of a given galaxy, because any deviation from unity can equally well be explained by an intrinsic colour gradient, especially for face-on galaxies (Byun et al., 1994).

In Chapter 5 we show that the mean scale length ratios for the later-type ($T > 2$) galaxies in our sample of edge-on disk galaxies range from $h_I/h_K = 1.15 \pm 0.19$ to $h_B/h_K = 1.65 \pm 0.41$, indicating large colour gradients in the disks.

Most previously published scale length ratios favour large colour gradients in galaxy disks:

- For a large sample of face-on galaxies Elmegreen & Elmegreen (1984) found a mean ratio of $h_B/h_I = 1.16 \pm 0.47$. Using Evans' (1994) models this corresponds to an average ratio of B to K-band scale length of about 1.32.
- Peletier et al. (1994, 1995a) present the results of a study of 37 Sb and Sc galaxies (uniform in orientation on the sky), for which they show that the B to K-band scale length ratio varies between 1.2 and 2, with a mean ratio of $h_B/h_K = 1.49 \pm 0.29$, comparable to our results.

– From de Jong's (1996a) scale length determinations of 86 face-on spiral galaxies, we find an average B to K-band scale length ratio $h_B/h_K = 1.22 \pm 0.23$

Large colour gradients in galaxy disks between B and I band have also been reported by Kent (1986). However, from a sample of 33 disk galaxies, van der Kruit (1991) reported a small scale length ratio between the photographic J and F bands, $h_J/h_F = 1.07 \pm 0.13$.

The main problem when comparing scale lengths and scale lengths ratios determined by different authors is the radial fitting range used to derive the scale lengths. However, if scale length ratios are calculated from scale lengths determined over the same range in each passband, the differences between different determinations should be $\sim 10\%$ at maximum (Peletier et al., 1994).

Peletier et al. (1994, 1995a,b) argue that scale length ratios due to stellar population changes are of order 1.1–1.2 in the blue – near-infrared range. Two lines of evidence were used to arrive at this result: first, from observations of $T < 1$ type galaxies without much visible dust by Balcells & Peletier (1994), it was found that $h_B/h_I = 1.04 \pm 0.05$, corresponding to B to K-band scale length ratios of at most $h_B/h_K = 1.08 \pm 0.10$, using stellar population models of, e.g., Arimoto & Yoshii (1986). From metallicity gradients from HII regions in galaxy disks, Peletier et al. (1994, 1995a) argue that h_B/h_K is likely of order 1.17, using a simple single-age stellar population model. In the I vs. K range this contribution is likely to be less. Our observations of the scale length ratios in our earliest-type sample galaxies ($T < 1$) support this evidence (Chapter 5)

Therefore, the observed scale length ratios in edge-on or highly-inclined disk galaxies largely represent the galaxies' dust content.

4.4 The influence of extinction

The effect of dust contamination on galaxy colours is that it causes reddening. The simplest way to predict the reddening of a given galaxy in a specific passband is to apply directly the Galactic extinction law (Rieke & Lebofsky, 1985). Physically, this corresponds to the situation in which we observe the galaxy through a foreground screen. However, by applying this foreground screen model to external galaxies, for a given reddening one underestimates the amount of dust present in these galaxies: a physically more realistic dust geometry for a galaxy is that it is mixed with the stars, so that on the near side of the galaxy a considerable fraction of stars will not or only slightly be affected by dust contamination. The most detailed of such dust models are the so-called "triplex" models proposed by Disney et al. (1989), in which a uniform mixture of dust and stars is embedded in a thicker and less dusty disk. If the dust resides in a disklike configuration, which could be approximated by an exponential dust distribution in both the vertical and the radial directions, the dust will redden the central parts of a galaxy more efficiently than the outer parts (e.g., Byun et al., 1994).

Disney et al. (1989) show that if the triplex model is valid, then galaxies will always behave as if optically thin, although the dust layer itself may be optically thick. On the other hand, Valentijn (1990) concludes, from extinction studies of a large sample of Sb-Sc galaxies, that galaxies not only are optically thick, but also behave optically thick over the entire disks. His methods were challenged by, among others, Huizinga & van Albada (1992), who argued that in his study Valentijn (1990) neglected the dependence of the effective light radius, r_e, and the D_{25} diameter on inclination.

The models that were discussed above treat the dust as a smoothly distributed, diffuse component. Huizinga (1994) and de Jong (1996b) considered the effects of non-homogeneous, clumpy dust distributions. From these studies they concluded that non-smoothly distributed, optically thick clouds will only be important if their filling factor is large. De Jong (1996b) remarks that in that case the models become comparable to his high optical depth models, which cause a reddening and a colour gradient, unless the clouds are optically thick at all wavelengths ("grey" dust).

If one assumes that the influence of dust contamination on colours can be approximated by the foreground screen model, the effect can easily be visualised in colour-colour diagrams by a "reddening vector". However, if more complex dust geometries are considered, or when scattering is included, the ratio between two colour excesses is not constant and the behaviour of the two colours follows a curved colour "trajectory" with increasing optical depth (Kuchinski & Terndrup, 1996). These trajectories lie roughly parallel to the classical reddening vector.

In general, one assumes that the dust properties of extragalactic dust are comparable to those of Galactic dust. Only a few studies of extragalactic extinction laws have been published (e.g., Knapen et al., 1991; Jansen et al., 1994), but they all seem to be consistent with the Galactic extinction law, except for a few measurements in the Small Magellanic Cloud. Although our knowledge of extragalactic dust properties is limited, Bruzual et al. (1988) argued that no large variations are expected, unless the extragalactic dust is of a completely different nature than that in our own Galaxy.

4.4.1 The effects of scattering on galaxy colours

If the dust is mixed with the stars, both absorption and scattering effects have to be taken into account. For simplicity, scattering effects are often neglected in studies of extinction in other galaxies.

Byun et al. (1994), using the method developed by Kylafis & Bahcall (1987), show that the error made by ignoring scattering effects decreases with inclination; at edge-on orientation scattering effects, at least the higher-order effects, can be ignored, because more light is scattered out of the plane of a galaxy disk than into the plane. Furthermore, the scattering effects are expected to be more important at shorter wavelengths, whereas they are probably not important in the near-infrared for highly-inclined galaxies (Kuchinski & Terndrup, 1996).

4.4.2 Near-infrared observations

Although there is still a significant amount of absorption in the near-infrared, even at K (Wainscoat et al. [1989] find that the K-band extinction in IC 2531 is $A_K \approx 0.3$ mag, whereas Rieke & Lebofsky [1985] find for the Galactic centre $A_K \approx 3$ mag), near-infrared photometry has some advantages compared to optical photometry. First, the near-infrared light is dominated by a population of old stars, presumably cool giants and dwarfs (e.g., Terndrup et al., 1994), which are much better tracers of a galaxy's mass distribution than the bluer, hotter stars in the spiral arms which dominate the optical luminosity (Aaronson, 1977; Frogel, 1988). However, it is probable that the K-band absorption is partially counteracted by emission from the young, newly formed stars in the galaxy plane. Secondly, in K the dust extinction is enormously reduced compared to that in the B band, which contributes to a better understanding of the true luminous (and mass) distribution in a given galaxy.

Finally, although one can expect the dust to induce reddening of a galaxy's colours, de Jong (1996b) cautions that the general direction in the colour-colour diagrams that is indicated by the dust models *for face-on galaxies*, is different from the overall trend seen in his sample of face-on disk galaxies. Therefore, the whole gradient cannot be caused by dust extinction, but an additional component is needed to explain the full gradient (for face-on galaxies).

4.5 Dust versus stellar population gradients

It is difficult to determine the physical process that causes the observed colour gradients unambiguously, since colour gradients produced by a change in metallicity (or stellar population) are parallel to those caused by reddening due to internal dust in a galaxy. Kuchinski & Terndrup (1996) therefore recommend the use of spectral line observations rather than broad-band colours to study these effects, because to date the exact behaviour of the dust component has not yet been established.

However, based on detailed modeling of broad-band observations of a large sample of face-on disk-dominated galaxies, de Jong (1996b), allowing for a range of dust properties, concludes that the observed colour gradients cannot be caused by reddening alone. His population models can predict both the right colours and also match the observed colour gradients closely, whereas the dust models can at best explain only the colour gradients.

All systematic colour differences induced by stellar population changes and metallicity gradients are generally considerably smaller than the reddening due to dust, however.

Finally, with the increasing availability of high-resolution observations, e.g., those done with the *Hubble Space Telescope (HST)*, we will be able to study the evolution of colour gradients by comparing the *HST* observations with observations of local galaxy samples.

5 Thesis Outline

At the time I started the project that has resulted in this Thesis, important problems that should be addressed were the effects of dust extinction in galaxy disks, and the vertical distribution of stars in the disks.

In order to study the effects of dust absorption observationally, we decided to observe a large, statistically complete sample of edge-on disk galaxies both in optical passbands and in the near-infrared, so that we could compare the surface brightness properties. This could reveal the vertical extent of the dust in galaxy disks. The only published near-infrared observations of an edge-on galaxy were those by Wainscoat et al. (1989), who studied the southern edge-on IC 2531. They found little evidence for dust at large distances from the galaxy plane, but in order to draw firm conclusions on the three-dimensional dust distribution, this should be investigated in a statistical way rather than based on individual cases.

In Chapter 2 I describe the selection criteria applied to select a statistically complete sample from the Surface Photometry Catalogue of the ESO-Uppsala Galaxies (ESO-LV; Lauberts & Valentijn 1989). Our final sample consists of 93 galaxies that are at least 87° inclined, have clear, undisturbed disks, and have a minimum blue major axis diameter of $D_{25}^B = 2.'2$. From this sample, we observed a subsample of 47 galaxies in B, V, and I, of which 24 were also observed in the near-infrared J and K' passbands, using the telescopes of the European Southern Observatory at La Silla in Chile. Finally, the data reduction techniques are discussed in detail and a comparison is made with published observations.

The second item of interest was the vertical distribution of stars in galaxy disks. Although the isothermal sheet approximation seemed to do well away from the galaxy planes, where optical observations are significantly influenced by dust contamination, some early results obtained from observations with near-infrared arrays indicated that at small distances from the galaxy planes an excess of light over the isothermal sheet model would be expected.

In Chapter 3 we test our reduction and analysis method by applying it to NGC 6504, for which we report both a radial dependence of the best-fitting vertical luminosity distribution and the detection of a clear thick disk with a scale height ~ 4 times the scale height of the dominant disk component.

Chapter 4 is an analysis of the structure parameters of a small pilot sample of northern-hemisphere edge-on galaxies. We introduce a global goodness-of-fit parameter which can be used to determine the best-fitting vertical luminosity and density distribution. Although we confirm that the vertical scale height seems to be relatively constant, in some cases it also seems to increase towards larger radii.

The fundamental galaxy parameters of our main sample are studied statistically in Chapter 5. As a side step, we have extended the absolute magnitude – colour relationship for lenticular and spiral galaxies towards the near-infrared, based on dust-free colours. The results of this study are presented in Chapter 6.

One of the most striking results from the global analysis in Chapter 5 is emphasized in Chapter 7, in which we report that, although the exponential disk scale height is constant to first order, for the large majority of our sample galaxies it increases with galactocentric distance. The effect is strongest for the earliest-type galaxies. We explain this increasing scale height by assuming that early-type galaxies have thick disks with both scale heights and scale lengths larger than those of the dominant disk component.

Chapter 8 describes our efforts to determine the z-structure of galaxies towards the galaxy plane unambiguously, in the K' band. We find that the mean levels of the sharpness of the vertical luminosity profiles lie in between the exponential and the intermediate sech(z) model (and may even be consistent with purely exponential vertical surface brightness profiles), with little variation along the galaxies' major axes or among galaxies of different types. We therefore argue that this implies that the process at work here is both global and universal.

In Chapter 9, we study the optical warp curves of our sample galaxies and compare the warp parameters as a function of wavelength.

Finally, in Chapter 10 I summarize our main results and look forward to future work in this field.

References

Aaronson, M., 1977, Ph.D. Thesis, Harvard University

Aaronson, M., Mould, J., 1985, ApJ 288, 551

Aoki, T.E., Hiromoto, N., Takami, H., Okamura, S., 1991, PASJ 43, 755

Arimoto, N., Yoshii, Y., 1986, A&A 107, 135

Baade, W., 1944a, ApJ 100, 137

Baade, W., 1944a, ApJ 100, 147

Bahcall, J.N., 1984a, ApJ 276, 169

Bahcall, J.N., 1984b, ApJ 287, 926

Bahcall, J.N., Kylafis, N.D., 1985, ApJ 288, 252

Bahcall, J.N., Soneira, R.M., 1980, ApJS 44, 73

Balcells, M., Peletier, R.F., 1994, AJ 107, 135

Barnaby, D., Thronson Jr., H.A., 1992, AJ 103, 41

Battaner, E., 1995, in: The Formation of the Milky Way, eds. Alfaro, E., Tenorio-Tagle, G., Cambridge: Cambridge Univ. Press, p. 77

Battaner, E., Florido, E., Sánchez-Saavedra, M.-L., 1990, A&A 236, 1

Battaner, E., Florido, E., Sánchez-Saavedra, M.-L., Prieto, M., 1991, in: Warped Disks and Inclined Rings Around Galaxies, eds. Casertano, S., Sackett, P.D., Briggs, F.H., Cambridge: Cambridge Univ. Press, p. 200

Bertin, G., Lin, C.C., 1987, in: Proceedings of the 10th IAU European Regional Astronomy Meeting, Prague, p. 255

Binney, J.J., 1978, MNRAS 183, 501

Binney, J.J., 1981, MNRAS 196, 455

Binney, J.J., 1991, in: Dynamics of Disk Galaxies, ed. Sundelius, B., Göteborg: Dept. Astron., Chalmers Univ., p. 297

Binney, J.J., 1992, ARA&A 30, 51

Bosma, A., 1990, in: Dynamics and Interactions of Galaxies, ed. Wielen, R., Berlin: Springer-Verlag, p. 356

Bosma, A., 1991, in: Warped Disks and Inclined Rings Around Galaxies, eds. Casertano, S., Sackett, P.D., Briggs, F.H., Cambridge: Cambridge Univ. Press, p. 181

Bottema, R., 1993, A&A 275, 16

Bottema, R., 1995, A&A 295, 605

Bottema, R., 1996, A&A 306, 345

Bottema, R., Shostak, G.S., van der Kruit, P.C., 1987, Nature 328, 401

Briggs, F.H., 1990, ApJ 352, 15

Bruzual, G.A., Magris, G.C., Calvet, N., 1988, ApJ 333, 673

Burke, B.F., 1957, AJ 62, 90

Burkert, A., Yoshii, Y., 1996, MNRAS, 282, 1349

Burstein, D., 1979, ApJ 234, 829

Burton, W.B., 1988, in: Galactic and Extragalactic Radio Astronomy, eds. Verschuur, G.L., Kellermann, K.I., New York: Springer, p. 295

Byrd, G.G., 1978, ApJ 226, 70

Byun, Y.I., Freeman, K.C., Kylafis, N.D., 1994, ApJ 432, 114

Carlberg, R.G., Sellwood, J.A., 1985, ApJ 292, 79

Cox, A.L., Sparke, L.S., van Moorsel, G., Shaw, M., 1996, AJ 111, 1505

de Jong, R.S., 1996a, A&AS 118, 557

de Jong, R.S., 1996b, A&A 313, 377

de Grijs, R., Peletier, R.F., 1997, A&A 320, L21 **(Chapter 7)**

de Grijs, R., Peletier, R.F., van der Kruit, P.C., 1997, A&A, in press **(Chapter 8)**

Dekel, A., Shlosman, I., 1983, in: Internal Kinematics and Dynamics of Galaxies, IAU Symposium 100, ed. Athanassoula, E., Dordrecht: Reidel, p. 187

Disney, M.J., Davies, J.I., Phillipps, S., 1989, MNRAS 239, 939

Djorgovski, S., Sosin, C., 1989, ApJ 341, L13

Dove, J.B., Thronson, Jr., H.A., 1993, ApJ 411, 632

Dubinski, J., Kuijken, K., 1995, ApJ 442, 492

Elmegreen, D.M., Elmegreen, B.G., 1984, ApJS 54,127

Evans, R., 1994, MNRAS 266, 511

Faber, S.M., 1973, ApJ 179, 731

Florido, E., Prieto, M., Battaner, E., Mediavilla, E., Sánchez-Saavedra, M.-L., 1991, A&A 242, 301

Forbes, D.A., DePoy, D.L., 1992, A&A 259, 97

Freeman, K.C., 1985, in: The Milky Way Galaxy, IAU Symposium 106, eds. van Woerden, H., et al., Dordrecht: Reidel, p. 113

Freudenreich, H.T., Berriman, G.T., Dwek, E., Hauser, M.G., Kelsall, T., Moseley, S.H., Silverberg, R.F., Sodroski, T.J., Toller, G.N., Weiland, J.L., 1994, ApJ 429, L69

Frogel, J.A., 1988, ARA&A 26, 51

Frogel, J.A., Persson, S.E., Aaronson, M., Matthews, K., 1978, ApJ 220, 75

Fuchs, B., Wielen, R., 1987, in: The Galaxy, Proceedings of the NATO Advanced Study Institute, Cambridge, England, eds. Gilmore, G., Carswell, R., Dordrecht: Reidel, p. 375

Gilmore, G., 1984, MNRAS 207, 223

Gilmore, G., Reid, N., 1983, MNRAS 202, 1022

Gilmore, G., King, I., van der Kruit, P.C., eds., 1989, The Milky Way as a Galaxy, Mill Valley: University Science Books

Gunn, J.E., 1982, in: Astrophysical cosmology, Proceedings of the Study Week on Cosmology and Fundamental Physics, Vatican City State, p. 233

Hamabe, M., Kodaira, K., Okamura, S., Takase, B., 1979, PASJ 31, 431

Hamabe, M., Kodaira, K., Okamura, S., Takase, B., 1980, PASJ 32, 197

Haywood, M., Robin, A.C., Crézé, M., 1997a, A&A 320, 428

Haywood, M., Robin, A.C., Crézé, M., 1997b, A&A 320, 440

Hegyi, D.J., Gerber, G., 1979, in: Photometry, Kinematics, and Dynamics of Galaxies, ed. Evans, D.S., Austin: Univ. of Texas Astron. Dept., p. 119

Hill, G., Hilditch, R.W., Barnes, J.V., 1979, MNRAS 186, 813

Hofner, P., Sparke, L.S., 1994, ApJ 428, 466

Huizinga, J.E., 1994, Ph.D. Thesis, Groningen University

Huizinga, J.E., van Albada, T.S., 1992, MNRAS 254, 677

Hunter, C., Toomre, A., 1969, ApJ 155, 747 **(HT69)**

Innanen, K.A., Kamper, K.W., Papp, K.A., van den Bergh, S., 1982, ApJ 254, 515

Jarvis, B.J., Freeman, K.C., 1985, ApJ 295, 324

Jansen, R.A., Knapen, J.H., Beckman, J.E., Peletier, R.F., Hes, R., 1994, MNRAS 270, 373

Jensen, E.B., Thuan, T.X., 1982, ApJS 50, 421

Kahn, F.D., Woltjer, L., 1959, ApJ 130, 705

Kent, S.M., 1986, AJ 91, 1301

Kent, S.M., Dame, T.M., Fazio, G., 1991, ApJ 378, 131

Kerr, F.J., 1957, AJ 62, 93

King, I.R., 1995, in: Stellar Populations, IAU Symposium 164, eds. van der Kruit, P.C., Gilmore, G., Dordrecht: Kluwer, p.337

Knapen, J.H., Hes, R., Beckman, J.E., Peletier, R.F., 1991, A&A 241, 42

Knapen, J.H., Beckman, J.E., Schlosman, I., Peletier, R.F., Heller, C.H., de Jong, R.S., 1995, ApJ 443, L73

Kronberg, P.P., 1994, Rep. Progress in Physics, 57:4, 325

Kuchinski, L.E., Terndrup, D.M., 1996, AJ 111, 1073

Kuijken, K., 1991, ApJ 372, 125

Kylafis, N.D., Bahcall, J.N., 1987, ApJ 317, 637

Lauberts A., Valentijn, E.A., 1989, The Surface Photometry Catalogue of the ESO-Uppsala Galaxies, ESO **(ESO-LV)**

Lacey, C.G., 1984, MNRAS 208, 687

Lynden-Bell, D., 1965, MNRAS 129, 299

May, A., James, R.A., 1984, MNRAS 206, 691

Morrison, H.L., Boroson, T.A., Harding, P., 1994, AJ 108, 1191

Nelson, R.W., Tremaine, S., 1995, MNRAS, 275, 897

Norris, J., 1987, in: The Galaxy, Proceedings of the NATO Advanced Study Institute, Cambridge, England, eds. Gilmore, G., Carswell, R., Dordrecht: Reidel, p. 297

Oort, J.H., 1932, Bull. Astron. Inst. Netherlands 6, 249

Ostriker, E.C., Binney, J.J., 1989, MNRAS 237, 785

Peletier, R.F., Balcells, M., 1996, AJ 111, 2238

Peletier, R.F., Balcells, M., 1997, New Astr. 1, 349

Peletier, R.F., Valentijn, E.A., Moorwood, A.F.M., Freudling, W., 1994, A&AS 108, 621

Peletier, R.F., Valentijn, E.A., Moorwood, A.F.M., Freudling, W., 1995a, in: The Opacity of Spiral Disks, ed. Davies, J., NATO Advanced Research Workshop, p. 243

Peletier, R.F., Valentijn, E.A., Moorwood, A.F.M., Freudling, W., Knapen, J.H., Beckman, J.E., 1995b, A&A 300, L1

Peletier, R.F., Willner, S.P., 1992, AJ 103, 1761

Porcel, C., 1997, Ph.D. Thesis, Universidad de Granada

Porcel, C., Battaner, E., 1995, MNRAS 274, 1153

Porcel, C., Battaner, E., Jiménez-Vicente, J., 1997, A&A 322, 103

Pritchet, C., 1983, AJ 88, 1476

Quinn, P.J., Hernquist, L., Fullagar, D.P., 1993, ApJ 403, 74

Quinn, P.J., Zurek, W.H., 1988, ApJ 331, 1

Rieke, G.H., Lebofsky, M.J., 1985, ApJ 288, 618

Rogstad, D.H., Lockhart, I.A., Wright, M.C.H., 1974, ApJ 193, 309

Rogstad, D.H., Wright, M.C.H., Lockhart, I.A., 1976, ApJ 204, 703

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

Saar, E., 1979, in: The large-scale structure of the Galaxy, IAU Symposium 84, ed. Burton, W.B., Dordrecht: Reidel, p. 513

Sancisi, R., 1976, A&A 53, 159

Sancisi, R., 1983, in: Internal Kinematics and Dynamics of Galaxies, IAU Symposium 100, ed. Athanassoula, E., Dordrecht: Reidel, p. 55

Sánchez-Saavedra, M.-L., Battaner, E., Florido, E., 1990, MNRAS 246, 458

Sasaki, T., 1987, PASJ 39, 849

Schweizer, F., 1976, ApJS 31, 313

Shaw, M.A., Gilmore, G., 1989, MNRAS 237, 903

Shaw, M.A., Gilmore, G., 1990, MNRAS 242, 59

Skrutskie, M.F., Shure, M.A., Beckwith, S., 1985, ApJ 299, 303

Sparke, L.S., Casertano, S., 1988, MNRAS 234, 873 **(SC88)**

Spitzer, L., 1942, ApJ 95, 329

Spitzer, L., Schwarzschild, M., 1951, ApJ 114, 385

Statler, T.S., 1989, ApJ 344, 217

Strom, S.E., Strom, K.M., Goad, J.W., Vrba, F.J., Rice, W., 1976, ApJ 204, 684

Strom, K.M., Strom, S.E., Jensen, E.B., Moller, J., Thompson, L.A., Thuan, T.X., 1977, ApJ 212, 335

Strom, K.M., Strom, S.E., Wells, D.C., Romanishin, W., 1978, ApJ 220, 62

Terndrup, D.M., Davies, R.L., Frogel, J.A., DePoy, D.L., Wells, L.A., 1994, ApJ 432, 518

Toomre, A., 1964, ApJ 139, 1217

Tóth, G., Ostriker, J.P., 1992, ApJ, 389, 5

Tsikoudi, V., 1979, ApJ 234, 842

Tubbs, A.D., Sanders, R.H., 1979, ApJ 230, 736

Valentijn, E.A., 1990, Nature 346, 153

van der Kruit, P.C., 1983, Proc. Astron. Soc. Australia 5, 136

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

van der Kruit, P.C., 1991, in: The World of Galaxies, eds. Corwin, H.G., Bottinelli, L., New York: Springer, p. 256

van der Kruit, P.C., Searle, L., 1981a, A&A 95, 105 **(KS1)**

van der Kruit, P.C., Searle, L., 1981b, A&A 95, 116 **(KS2)**

van der Kruit, P.C., Searle, L., 1982a, A&A 110, 61 **(KS3)**

van der Kruit, P.C., Searle, L., 1982b, A&A 110, 79 **(KS4)**

van Dokkum, P.G., Peletier, R.F., de Grijs, R., Balcells, M., 1994, A&A 286, 415 **(Chapter 3)**

Wainscoat, R.J., Freeman, K.C., Hyland, A.R., 1989, ApJ 337, 163

Wainscoat, R.J., Hyland, A.R., Freeman, K.C., 1990, ApJ 348, 85

Wielen, R., 1977, A&A 60, 263