University of Groningen

Structure and kinematics of edge-on galaxy disks

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2003

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Kregel, M. (2003). *Structure and kinematics of edge-on galaxy disks*. s.n.

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Introduction

THROUGHOUT human history attempts have been made to grasp the meaning of the faint narrow band of whitish light seen winding across the entire sky. Remarkably, the construction of a scientific framework for the appearance of this ‘Milky Way’ was already initiated during the period of the Enlightenment, much earlier than the techniques necessary to carry out detailed observational programs. Based on a conjecture by Thomas Wright, the philosopher Immanuel Kant suggested in 1755 that the Milky Way is a vast collection of stars, flattened by systematic rotation and upheld by Newton’s force of gravity. He went on to argue that the occurrence of stars away from the symmetry plane of the Milky Way indicates that these stars lie on more erratic orbits. Most strikingly, Kant further envisioned that the similarly faint, much smaller nebulae were distant ‘island universes’ like our Milky Way.

Since then, the ongoing acceleration of advances in observational instrumentation and the simultaneous branching and expansion of theoretical astrophysics have not just confirmed Kant’s reasoning, but tremendously improved our understanding of the nature of the galaxies. Galaxies are highly diverse entities that come in different shapes and sizes, and have both inborn characteristics as well as traits fostered by their environment. The centrifugally supported disks of the spiral galaxies, of which our Milky Way is the prime example, form a most conspicuous element within the galaxy population. These flattened structures point to a common evolutionary history undisturbed by major galaxy interactions and form the purest end-product of galaxy formation.

The constituents of galaxy disks can be loosely categorized into two groups: a young disk or layer consisting of the gaseous interstellar medium and young stellar populations (with ages less than a few Gigayears), and an old disk consisting of the older stellar populations (among which our sun). In radius, the young disk is often more extended than the old disk. In mass, the young disk is dominated by the hydrogen clouds (atomic and molecular). These clouds are highly dissipative and trace nearly circular orbits, making the inner parts of the young disk highly flattened. The old disk, on the other hand, is dynamically hotter, thicker and contains the bulk of the luminous matter. In essence, old disks form the fossil record of the processes governing the formation and evolution of galaxy disks.

Galaxy disks attract much attention because the circular-speed curves of the young, dynamically cold disks form a reliable tracer of the radial distribution of mass. The neutral hydrogen (H I) circular-speed curves remain flat out to radii far beyond the stellar disk. This observation demonstrates unambiguously that spiral galaxy disks are embedded within halos of unseen matter. Unfortunately, poor understanding of the amount of matter in the luminous disks themselves has hampered our understanding of the structure of these dark matter halos. The disk mass budget also plays a key role in our understanding of the disks themselves, as well as in the interrelation between disks and dark halos. Examples are dynamical disk stability, the possibility of the presence of dark matter within disks and the origin of the tight relation between disk luminosity and galaxy rotational velocity, all of which trace back to the processes of disk galaxy formation and evolution. Clearly, it is of great importance to put constraints on the disk mass.

In this thesis, attention is focussed on the global structure and kinematics of the old stellar disks of spiral galaxies. The ultimate goal is to study the disk masses by applying the principles of stellar dynamics to the observations. To this end, galaxy disks are addressed from an observational perspective, and by taking an edge-on view. Before embarking on an outline of this approach and commenting on its virtues and vices, first our current knowledge on the global structure and kinematics of stellar disks is summarized.[*]

1.1 Background

1.1.1 The age-old shining disk

Stellar disks are strikingly inhomogeneous systems. Across the face of the disk the surface brightness diminishes by about four magnitudes. The basic shape of this radial decline is exponential in most spiral galaxies (de Vaucouleurs 1959; Freeman 1970). In the local universe, the scalelength of the disk light (the radial distance over which the brightness decreases by a factor *e*) attains values between roughly one and twenty kiloparsecs, depending on the galaxy's maximum rotational velocity and the disk central surface brightness (Graham 2002). If the disk mass-to-light ratio is almost constant with galactocentric radius, as suggested by the shallow radial color gradients in the disk (de Jong 1996b), then the disk mass distribution is also approximately exponential. This suggests that the exponential form has a generic origin. It is not yet clear whether the exponential is either a footprint of the settling of gas during the collapse of the protogalaxy (Fall & Efstathiou 1980; Dalcanton, Spergel, & Summers 1997) or the result of secular re-distribution of angular momentum within the disk (Lin & Pringle 1987; Thon & Meusinger 1998).

In addition to the exponential decline, the disk light shows a steeper drop at large galactocentric radii (van der Kruit & Searle 1982; Pohlen et al. 2000b, for the Milky Way see Drimmel & Spergel 2001). This stellar disk truncation or cut-off is most easily detected in edge-on spirals because of their higher surface brightness. The location of the stellar disk edge constitutes an important constraint on theories of disk formation and evolution. For example, it may reflect the maximum specific angular momentum of the protogalaxy (van der Kruit 1987), or correspond to the radius at which the gas density drops below a threshold value necessary for wide-spread star formation (Fall & Efstathiou 1980; Kennicutt 1989).

Stellar disks consist of various generations of stars, such that the vertical light distribution is the result of an intricate convolution of the histories of star formation and dynamical heating and the evolution of the initial mass function (Bahcall 1984a; Haywood, Robin, & Créze 1997). Hence, the disk is a stratified structure, with young stellar populations being confined

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[*] Hereafter, the old stellar disk is often loosely referred to as the stellar disk.

to the galaxy plane and the old stellar populations dominating at sufficiently large distances from the plane. The fact that the stellar mass-to-light ratio (M/L) rapidly increases with age strongly suggests that the old stellar disk dominates the disk mass budget. This old disk light shows a vertical decline which is approximately exponential, with an exponential scaleheight roughly ten times smaller than the radial scalelength (van der Kruit & Searle 1982; Shaw & Gilmore 1990). In the solar neighborhood the scaleheight of the old disk light is probably close to the thickness of the disk mass distribution (Siebert, Bienaymé, & Soubiran 2003). Remarkably, despite the large drop in stellar density, the old disk scaleheight is approximately constant with radius (van der Kruit & Searle 1981a; de Grijs & Peletier 1997, for the Milky Way see Kent, Dame, & Fazio 1991).

Stellar disks are truly three-dimensional structures, and their vertical structure is needed to fully understand internal processes such as star formation and disk heating. In addition, dynamical estimates of the disk mass rely on the principle of vertical dynamical equilibrium (i.e. hydrostatic equilibrium). This states that the amount of mass contained in the disk is proportional to the ratio of the stellar velocity dispersion (i.e. the spread in stellar velocities) and the disk scaleheight. Hence, the scaleheight is of considerable importance for dynamical estimates of the disk mass. Although several studies of edge-on spiral galaxies have addressed the scaleheight of the old disk light, at present little is known about the scaleheights among galaxy disks. Similarly, there are indications that the flattening of the stellar disk (i.e. the ratio of scalelength to scaleheight) increases slowly with Hubble type (Guthrie 1992; de Grijs 1998). Further study of the disk scaleheight and the disk flattening as a function of other global galaxy properties is needed.

1.1.2 Older, slower, and more erratic…

In the solar neighborhood, the spread in the velocities of the stars of a coeval population increases with the population's age (Parenago 1950; Wielen 1977). This trend can be explained by the gravitational scattering of stars off density enhancements within the disk, such as giant molecular clouds (Spitzer & Schwarzschild 1951, 1953) and spiral arms (Barbanis & Woltjer 1967). In addition, secular heating due to satellite accretion (Velazquez & White 1999) may play a role. In this way, coeval populations become increasingly well-mixed with increasing age, such that their velocity distributions can be approximated by a simple velocity ellipsoid (a trivariate Gaussian, Schwarzschild 1907). In particular the old disk can be identified with a homogeneous population of stars having ages between three and ten Gigayear, metallicities [Fe/H] of -0.6 to $+0.2$, and in essence a single velocity ellipsoid (Freeman 1991). In the solar neighborhood the velocity ellipsoid of the old disk has its long axis pointing towards the Galactic center, and its velocity dispersions in the three principal directions are $\sigma_{\rm R} : \sigma_\phi : \sigma_{\rm z} = 1.0 : 0.7 : 0.5$ with $\sigma_{\rm R} \simeq 35$ km s^{-1} (Wielen 1974; Dehnen & Binney 1998).

An important point that follows from these solar neighborhood studies is that the kinematics of a sufficiently large sample of old disk stars are well described by a velocity ellipsoid. This corresponds to what can be observed in nearby galaxies, because there a ground-based telescope samples on the order of a million stars per spatial resolution element. Since, in addition, the optical spectra of normal spiral galaxies are dominated by evolved stars (longward of 5000 Å, Kennicutt 1992), a composite spectrum at a single position in a stellar disk is essentially that of a star typical of the evolved population convolved with the line-of-sight component of the velocity ellipsoid. The kinematics of the old stellar disk can thus be probed using the stellar absorption lines (Kormendy 1984; van der Kruit & Freeman 1984).

Stellar disk rotation curves derived in this way from deep long-slit galaxy spectra show the same general shape as those of the gas, yet with lower amplitude (Bottema 1993; Gerssen, Kuijken, & Merrifield 2000, for the Milky Way see Lewis & Freeman 1989). This phenomenon is widely known as the asymmetric drift (first recognized in the Milky Way by Strömberg, 1924). Depending of the amount of energy invested in random motion, most stars follow rosette-shaped orbits at an azimuthal velocity lagging the circular speed. The stellar disk velocity dispersions decrease with galactocentric radius, with an exponential scalelength roughly twice times the scalelength of the disk light (van der Kruit & Freeman 1984, 1986; Bottema 1993). The data further suggest that the shape of the velocity ellipsoid does not change strongly throughout the old disk. An independent observational argument for the approximate constancy of the shape of the velocity ellipsoid comes from the detailed ages and kinematics of 182 F and G dwarf stars in the solar neighborhood (Edvardsson et al. 1993). These indicate that the ellipsoid shape was set after an early heating phase and, though the Galaxy has probably changed much over its lifetime, has remained constant throughout the life of the old disk (Freeman 1991).

1.1.3 Weighing disks

Although stellar disks are dynamically slowly evolving, they are collisionless on a dynamical time scale (the time-scale of a single galactic revolution). Hence, stellar disks are in a quasi-equilibrium state, such that their kinematics contain information regarding the gravitational potential. Thus, when combined with the principles of stellar dynamics, the stellar disk kinematics can be used to constrain the disk mass distribution. Despite its potential, this technique has been applied for only a handful of galaxies (Bottema 1993). The reason is practical: stellar disks are faint, requiring a considerable observational effort to retrieve their kinematics.

Nonetheless, for twelve normal (= unbarred) high surface brightness disks Bottema (1993) noticed a correlation between the amplitude of the stellar disk velocity dispersion and the galaxy maximum rotational velocity ($v_{\rm max}$). This $\sigma - v_{\rm max}$ relation suggests that the stellar disks of more massive spirals are dynamically ‘hotter’. A comparison with the relation for isolated exponential disks indicates that the peak rotation of the disk is on average only 63±10 percent of the observed maximum rotation (Bottema 1993). This important result implies that the disk mass is a factor of two lower than in the hypothetical maximum-disk situation (van Albada & Sancisi 1986). In other words, disks appear to be submaximal. The submaximality of disks is consistent with the tightness of the Tully-Fisher relation for disks of different central surface brightness (Courteau & Rix 1999). Since the dynamical disk M/L corresponding to the 63% result is in the lower part of the range of the stellar M/L according to population synthesis models (Bell & de Jong 2001), submaximal disks would further imply that there is not much room for dark matter within disks. This is consistent with dynamical studies of the solar neighborhood (Kuijken & Gilmore 1991; Siebert et al. 2003).

Simultaneously, submaximal disks imply that the dark matter halo dominates the mass fraction down to small galactocentic radii. This is in agreement with numerical and analytical models of disk galaxy formation within dark matter halos, which predict that the dark matter is dominant down to radii of around one disk scalelength (Dalcanton et al. 1997; Mo, Mao, & White 1998). Unfortunately, the observational result is still ill-constrained due to the small number of spirals for which the stellar disk velocity dispersions are known. In addition, Bottema’s (1993) argument assumes that the average disk flattening is about ten, something which also has not yet been investigated using a statistically significant galaxy sample. If the $\sigma - v_{\max}$ relation and the assumed average disk flattening could both be confirmed, the case for the presence of a large amount of dark matter in the inner parts of spiral galaxies would strengthen considerably.

1.1.4 The edge-on perspective

Edge-on spiral galaxies are notorious for having the very elements which complicated early twentieth century Galactic astronomy – dust extinction and line-of-sight integration (i.e. a sight line passes through the entire disk). The recognition and confrontation of these difficulties using various observational techniques has greatly improved our understanding of the structure and dynamics of the Milky Way. Similarly, the construction of a coherent framework which recognizes the complementary properties seen in the edge-on and the face-on view is fundamental to understand the physical processes governing spiral galaxies in general.

In recent years, various techniques have been developed to study the dust distribution and line-of-sight projection in edge-on spirals. The detailed study of individual edge-on spirals has provided valuable insights regarding the opacity of spiral galaxies. Detailed radiative transfer modeling of edge-on spirals in the optical, infrared and submillimeter have established that the bulk of the dust is confined to the galaxy plane, with a scaleheight about half times that of the stellar disk (Kylafis & Bahcall 1987; Alton et al. 2000). These as well as recent statistical studies of large numbers of spirals of different orientations (Giovanelli et al. 1995; Tully et al. 1998) are converging on the view that massive spirals are optically thick in their centers, with face-on central optical depths around unity in the optical, and transparent in the outskirts. Dwarfs and low surface brightness spirals appear to be transparent throughout (Matthews & Wood 2001). As an important corollary, in edge-on spirals the old disk can be studied at a sufficient distance from the plane without having to account for large amounts of dust extinction. The influence of residual dust extinction can be inferred from a comparison of the rotation curve derived from the optical emission lines with that of dust-free tracers such as H I or CO (Bosma et al. 1992).

Stellar disks are not axisymmetric in detail, showing lopsidedness, spiral structure and in some cases warping (Rix & Zaritsky 1995; de Grijs 1997). Still, these deviations from axisymmetry are often small: the basic radial behavior of the disk structure and kinematics can be studied by selecting against irregular spirals and assuming axisymmetry. Hence, the surface brightness distributions and line-of-sight kinematics of stars and gas of edge-on galaxies can be corrected for the effect of projection. This has opened up, for example, the study of the three-dimensional disk luminosity distribution (van der Kruit & Searle 1981a) and the stellar disk kinematics of edge-on spirals (Bottema, van der Kruit, & Freeman 1987).

Besides allowing a direct measurement of the disk scaleheight, edge-on spirals have a number of observational advantages that are often not fully recognized. First, the line-of-sight integration ensures that the disk surface brightness is substantially higher when seen edge-on, at least away from a dust lane. This brightening is proportional to the flattening of the disk and can easily amount to two magnitudes arcsec^{-2}. Hence, when viewed edge-on, disks can be more easily studied at larger galactocentric radii and out to larger cosmological distances. This effect also facilitates the study of disks with a low *face-on* surface brightness. Secondly, the stellar velocity distribution is broadened by the velocity gradient across an edge-on disk. This allows the detection of lower intrinsic velocity dispersions in edge-on systems with the same instrumental setup, typically by a factor of two. Thirdly, the line-of-sight integration means that effectively the entire galaxy plane is sampled by a single slit. This ensures that local irregularities present in the stellar density and kinematics, such as spiral structure (Misiriotis et al. 2000), are largely averaged out.

1.2 This Thesis

1.2.1 Goals

The prime objective of this study is to provide new constraints on the dynamics of spiral galaxy disks through an observational synthesis of the global stellar disk structure and kinematics. The importance of the vertical disk structure for the estimating the disk masses automatically brings the aim toward edge-on systems. The wish to study 'pure' disks further narrows the focus toward undisturbed spirals of intermediate- to late- Hubble type. By combining photometry, absorption line spectroscopy and H I synthesis observations for a substantial sample of such spirals, the properties of galaxy disks can be probed over a large range in maximum rotational velocity and surface brightness. For such a sample, optical and near-infrared photometry has been analyzed by de Grijs (1998). This sample has been adopted as a starting point for the present study.

As may be appreciated from Sect. 1.1, such data touches upon many fundamental questions. Does the stellar disk thickness relate to the size of the galaxy? Is the flattening of the disk linked to other global galaxy properties? At what radius do stellar disks truncate and why? Is there indeed a trend between the amount of random stellar motions and the rotational velocity of a galaxy? If so, what is physical cause of this relation? Is the matter in the disk sufficient to explain the rotation curve in the inner parts of spiral galaxies? And finally, how do the answers to the above questions change for disks of lower surface brightness? In this thesis, specific attention will be given to the disk flattening, the stellar disk truncations, the stellar kinematics, and the gaseous rotation curves. For example, combining the stellar velocity dispersions with the gas rotation curve will significantly increase the statistics on the $\sigma - v_{\max}$ relation. Ultimately, the data will be used together with a dynamical model to address the (sub)maximal nature of galaxy disks.

1.2.2 Brief outline

In Chapter 2, the global structure of the old thin disks is analyzed using a two-dimensional decomposition technique, which takes into account the effects of dust attenuation, projection and a possible radial truncation. The derived disk parameters, especially the flattening of the disks, are investigated with respect to other global parameters. A re-evaluation of the Bottema (1993) argument is made using the observed distribution of the disk flattening. In Chapter 3, the stellar disk light is investigated for the presence of a radial truncation. The results are compared to the predictions of several scenarios for the origin of the stellar truncation.

Chapter 4 is devoted to the new optical long-slit spectroscopic observations obtained with the SSO 2.3m, the WHT and the VLT. The stellar kinematics are extracted from the stellar absorption lines in these spectra using the improved cross-correlation technique. The results are discussed individually as well as generally. For the same spirals, new H I synthesis observations obtained using the ATCA and the WSRT are described in Chapter 5. This chapter describes the observations and their reduction, and summarizes an analysis of the properties of the H I. Specific attention is given to the methods for determining the gaseous rotation curves of edge-on spirals.

In Chapter 6 the rotation curves are investigated. A new technique is introduced for determining a gaseous rotation curve. The technique is applied to the H I observations of eight spirals of sufficient quality. The H I rotation curves for the full sample are further augmented with the optical emission line kinematics. First, the two kinematical tracers are compared in order to infer the effect of dust extinction on the optical kinematics. Second, they are combined in order to estimate the full rotation curves.

To study the dynamical properties of the stellar disks, the three-dimensional disk structure, the stellar kinematics, and the rotation curves of fifteen edge-on spiral galaxies are modeled in Chapter 7. First, simulations of three-dimensional disks that include a realistic radiative transfer prescription are investigated for the effects of dust extinction and projection. Then, the dynamical model is matched to the observations, yielding for each galaxy the intrinsic stellar disk kinematics and the disk mass. These data are finally analyzed with respect to the $\sigma - v_{\rm max}$ relation and the disk contribution to the rotation curve.