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Structure and kinematics of edge-on galaxy disks

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Summary and Outlook

THESIS ABSTRACT — The structure and kinematics of spiral galaxy disks are addressed from the edge-on perspective. An *I*-band analysis of the thin disk structure of 34 edge-on spirals confirms that the disks of spirals with a larger maximum rotational velocity are generally thicker. The data reveal a remarkable relation between the disk flattening, its face-on central surface brightness and the galaxy dynamical mass-to-light ratio. Apparently, the three dimensional disk shape is intimately tied to the prominence of the dark matter halo. Many stellar disks are radially truncated, with the disk edge occurring at a shorter number of scalelengths in disks with a lower face-on central surface brightness. This observation suggests that the truncation is caused by a star formation threshold. New optical spectra and H I synthesis observations are used to determine the line-of-sight stellar kinematics and the gaseous rotation curves for half of the spirals in the sample. A detailed comparison of the H I and H II kinematics shows that dust extinction does not affect the optical kinematics at galactocentric radii beyond about one disk scalelength. Dynamical modeling of the combined data is used to determine the intrinsic stellar disk kinematics and estimate the disk masses. At least twelve out of thirteen disks are sub-maximal, with an average disk contribution to the galaxy rotation curve of 53 ± 4 percent. Seven of these spirals have either a boxy- or peanut-shaped bulge, strongly suggesting that the submaximal nature of disks is independent of barredness. It is confirmed that the stellar disk velocity dispersion tends to increase with the galaxy maximum rotational velocity. Moreover, the scatter in this relation correlates with disk flattening, central surface brightness and the dynamical mass-to-light ratio. The findings are in general accordance with the collapse theory of disk galaxy formation. Future research should target the link between disk flattening, surface brightness and dynamical mass-to-light ratio and strive to make stellar kinematical observations and modeling a routine.

8.1 Inventory

The main goal of this thesis was to provide new observational constraints on the dynamics and masses of galaxy disks. To this end edge-on galaxy disks were targeted, providing the unique opportunity to take into account the three-dimensional disk shapes. The existing photometry of the edge-on galaxy sample of de Grijs (1998) served as a starting point.

8.1.1 Disk structure

Lenticulars and spirals with clearly warped or lopsided stellar disks were excluded from the de Grijs (1998) sample, yielding a sample of 34 regular edge-on spiral galaxies. This sample is dominated by intermediate- to late-type spirals and covers a large range in maximum rotational velocity. The global structure of the old thin disks of these spirals was analyzed in the *I*-band using a two-dimensional decomposition technique (Chapter 2).

The average volume-corrected flattening of the disk light is $\langle h_R/h_z \rangle = 7.3 \pm 2.2$ (1σ). This result was used to re-estimate the disk contribution to the rotation curve implied by the stellar kinematics of 12 high surface brightness (HSB) disks (Bottema 1993). If the old disk light is as flattened as the disk mass then the disk contribution is only 57 ± 22 percent, confirming Bottema's (1993) conclusion.

The scaleheight of a stellar disk is found to increase as a function of maximum rotational velocity and total dynamical mass. This is in qualitative agreement with the correlation between the stellar disk velocity dispersion and galaxy maximum rotational velocity reported by Bottema (1993). To first order, spirals with a larger rotational velocity harbor disks that are more dynamically evolved and thicker.

The deprojected face-on central surface brightnesses of the disks cover a range of three magnitudes, well into the low surface brightness (LSB) regime. Lower surface brightness disks have a progressively larger dynamical mass-to-light ratio, as in face-on spirals (de Blok, McGaugh, & van der Hulst 1996). This is in accordance with the observation that the Tully-Fisher relation is independent of disk surface brightness (Zwaan et al. 1995; Verheijen 2001). Remarkably, disks with a lower surface brightness and a larger dynamical mass-to-light ratio are also more flattened. This observation presents a new link between the three-dimensional shape of the disk and the prominence of the dark halo: flatter disks appear to be embedded within more massive dark halos. These results predict that the vertical stellar velocity dispersions of lower surface brightness disks are smaller.

The *I*-band photometry was investigated for the presence of radial stellar disk truncations (Chapter 3). In most spiral disks a radial truncation is detected. The ratio of truncation radius to disk scalelength is on average $R_{\text{max}}/h_R = 3.6$ with a scatter of 0.6 (1σ). Smaller spirals appear to truncate at relatively large radii (in terms of scalelengths), which may partly explain why radial truncations are not easily observed in face-on spirals. In addition, lower surface brightness disks tend to truncate at a smaller number of disk scalelengths. These observations are best reproduced by a gas density threshold on star formation (Schaye 2002).

8.1.2 Disk kinematics

For half of the galaxies in the sample deep optical spectra were gathered with the SSO 2.3m, the WHT and the VLT (Chapter 4). The line-of-sight stellar kinematics were extracted from the stellar absorption lines using the cross-correlation technique. In general, the stellar kinematics are regular and can be traced well into the disk-dominated region. In four spirals, with a peanut- or boxy-shaped bulge, asymmetric velocity distributions are detected. In two cases, ESO 240-G11 and NGC 5529, these asymmetries probably represent the 'figure-of-eight' pattern synonymous of a barred potential (Kuijken & Merrifield 1995; Bureau & Athanassoula 1999). In general, however, the asymmetries may also be due to the projected disk.

For the same spirals, radio synthesis observations were performed with the ATCA and the WSRT to study the HI distribution and kinematics (Chapter 5). The HI is distributed

regularly, showing no strong warping or massive companions. The exception is the barred spiral NGC 5529, which is perturbed in both the optical and the H I and has two companions connected to the main galaxy via H I bridges.

A new technique is introduced for extracting the rotation curves from the entire major axis position-velocity diagram (Chapter 6). The technique was successfully applied to the H I observations of eight spirals with sufficient signal-to-noise ratio, and revealed the rising part of the rotation curve for two spirals. The H I rotation curves for the full sample were augmented with the optical emission line (H II) kinematics in order to arrive at the full rotation curves. A detailed comparison of the H I and H II kinematics confirms that intermediate to late-type edge-on spirals are transparent in the outer parts (Bosma et al. 1992). The H II is often mainly confined to spiral arms and does not extend out to the edge of the H I layer, causing the H II velocity profiles to be significantly narrower than those of the H I.

8.1.3 Disk dynamics

The stellar kinematics, the three-dimensional stellar disk structure, and the gaseous rotation curves of fifteen edge-on spiral galaxies were modeled to study the dynamical properties of their stellar disks (Chapter 7). Simulated disks that include a realistic radiative transfer prescription were first investigated. This confirmed that for face-on optical depths around unity (Xilouris et al. 1999) the projected kinematics are practically dust free at the studied slit positions.

In thirteen cases the dynamical model provides a good match to the observed stellar disk kinematics. Nearly all of these spirals have submaximal disks: maximum disks would require $\sigma_z/\sigma_R \simeq 1$ and imply Q values below unity, which is unphysical (Toomre 1964). For $\sigma_z/\sigma_R = 0.6$ the average disk contribution at 2.2 disk scalelengths is 53 ± 4 percent with a 1σ scatter of 15 percent, confirming the work of Bottema (1993). Hence, only about forty percent of the total mass within 2.2 disk scalelengths resides in the disk. The average contribution for the six spirals with a boxy- or peanut-shaped bulge is 56 ± 9 percent, indistinguishable from the normal spirals. Since boxy- and peanut-shaped bulges are probably associated with bars (Kuijken & Merrifield 1995; Bureau & Freeman 1999), this strongly suggests that the contribution of the disk to the rotation curve is independent of barredness.

A reference value for the stellar disk velocity dispersion tends to be larger in spirals with a higher maximum rotational velocity, as in the sample of Bottema (1993). This is probably the result of local dynamical stability: more massive spirals harbor more massive disks, which in order to remain stable have developed higher stellar disk velocity dispersions. The scatter in this $\sigma - v_{\max}$ relation is found to correlate with disk flattening, face-on central surface brightness and total dynamical mass-to-light ratio. Disks with a smaller radial stellar velocity dispersion tend to be more flattened, have a lower surface brightness and a higher dynamical mass-to-light ratio. This is in good agreement with the relation between disk flattening and dynamical mass-to-light ratio (Chapter 2).

Finally, the disk mass Tully-Fisher (TF) relation is compared to the maximum-disk scaled stellar mass TF relation of the Ursa Major cluster (Bell & de Jong 2001). The dynamical disk mass TF is offset from the maximum-disk scaled stellar mass TF relation by -0.3 dex in mass. The offset is mirrored in the baryonic TF relations and is naturally explained when the disks of the Ursa Major cluster spirals are submaximal.

The submaximal nature of galaxy disks, the $\sigma - v_{\max}$ relation and the three-parameter relation between central surface brightness, dynamical mass-to-light ratio and disk flattening

are in good agreement with the theory of the formation of disk galaxies in virialized dark matter halos (Dalcanton, Spergel, & Summers 1997; Mo, Mao, & White 1998). In this picture, disks make a range of contributions to the maximum rotation, from strongly submaximal in halos of higher than average spin angular momentum toward less submaximal in halos of low spin angular momentum. The scatter in the $\sigma - v_{\text{max}}$ relation results from the spread in halo spin parameters and the stability parameter Q . According to the collapse model the observed trend that disks with a lower stellar velocity dispersion disks tend to be flatter, of lower central surface brightness and of higher dynamical mass-to-light ratio represents the increasingly extended disks that arise from higher spin angular momentum dark halos.

8.2 Questions and suggestions

A scientific inquiry raises more questions than it answers. These questions are one of the most exciting facets of doing science, and inspire new paths of research, which in turn are bound to raise more questions and sometimes even yield a breakthrough or discovery. This section summarizes the important questions which arose during this research and offers suggestions for obtaining answers.

The remarkable correlation found between disk flattening and dynamical mass-to-light ratio carries potential for estimating the disk flattening in face-on spirals, which is needed to obtain accurate dynamical estimates of their disk surface densities. It also constitutes a new constraint for theoretical models of disk galaxy formation and numerical simulations of isolated spirals. Therefore, the zero point, slope and intrinsic scatter of the relation between flattening and dynamical mass-to-light ratio need to be firmly established. This calls for high resolution near-infrared photometry of almost exactly edge-on disks (with inclinations higher than 88 degrees) with accurate distances and rotation curves. Note that the inclination will be difficult to determine for small and low surface brightness spirals because they often do not show an optical dust lane. Perhaps ultraviolet imaging or high resolution velocity fields of the gas can be used to reliably determine their inclination.

By constraining the contribution and vertical distribution of young red supergiants in the near-infrared, using e.g. the $2.3 \mu\text{m}$ CO index (Rhoads 1998), one can also use the near-infrared photometry to study the exact shape of the vertical density distribution of the old disk close to the plane. When extended to the optical it becomes possible to constrain the detailed shape of the vertical disk light, dust and disk mass profiles. This will also further elucidate the offset between the classic luminosity Tully-Fisher relations of edge-on and face-on spirals.

The existence of radial disk truncations is now well established. The most likely physical origin is a star formation threshold (Schaye 2002). Future work should therefore focus on the relation between disk surface brightness and truncation radius in less-inclined spirals, and on a more local scale. Very deep imaging, both broadband and $\text{H}\alpha$, for a small dedicated nearby sample of regular field spirals covering a wide range in disk central surface brightness is needed. These spirals can be selected based on existing high resolution H I synthesis observations.

A Hubble tuning fork for edge-on spirals is largely missing. Currently, morphological classification of edge-on spirals is solely based on visual bulge-to-disk ratios. The bulge to disk ratios should be quantified in the near-infrared and then compared to those of face-ons. The signatures of bars in the major axis position-velocity diagrams will probably improve the classification of bars in edge-on spirals in the near future. A similar approach can perhaps also

constrain the prominence and shapes of spiral structure. The non-axisymmetric structures in the position-velocity diagrams of edge-on spirals can be classified empirically by integrating existing $H\alpha$ and/or HI data cubes of intermediately inclined galaxies perpendicular to the major axis and comparing the resulting position-velocity diagrams.

An obvious subject of future study is the extension of the $\sigma - v_{\max}$ relation to a larger range in surface brightness, maximum rotational velocity and morphological type. For HSB disks and edge-on LSB disks the required observations can now be routinely obtained using 10 meter class telescopes, taking typically only one hour of observations per galaxy. Determining the stellar disk kinematics of face-on LSB systems is more demanding. It will require deeper observations at higher spectral resolution as well as a more sophisticated dynamical model that includes (self-consistently) the gas layer and the dark halo. Similar challenges await the study of the stellar dynamics in the outer parts of HSB spirals.

Measurements of the stellar kinematics can be further combined with an estimate of the disk flattening from edge-on spirals to pin down the disk mass distribution. By studying galaxies with accurate distances and excellent rotation curves, such a study will significantly improve our knowledge of the stellar disk mass and baryonic mass Tully-Fisher relations, and finally allow a confident investigation of the radial distribution of the dark matter. It will also yield estimates of the stellar velocity anisotropy (σ_z/σ_R), which can be used to further address disk heating as well as the disk masses of edge-on spirals.

Five years ago, edge-on spiral galaxies were being widely dismissed as merely obscured and complicated. Steadily though, the edge-on view is filling up a large gap in our understanding of spiral galaxies: the vertical dimension. Most importantly, it is revealing the three-dimensional shapes of the dust and gas layers, disks, bulges, bars and dark matter halos. These shapes are becoming increasingly important for a better understanding of the dynamics of, and the interplay between, these components, and ultimately the origin and future of the spiral galaxies.

