

Chapter 5

Properties of Disk Galaxies

Disk galaxies are typically composite systems, built from several *stellar populations*. Besides a thin, rotating disk, such galaxies often include thicker disks or spheroids.

5.1 Photometry

Radial profiles of many disk galaxies can be fit quite accurately by a superposition of an exponential disk and de Vaucouleurs bulge (e.g. Boroson 1981). Although such decompositions are often non-unique, the results support the notion that disk galaxies are composite systems.

5.1.1 Disk luminosity distribution

Outside of their centers, disk galaxies typically have exponential luminosity profiles:

$$I(R) = I_0 \exp(-R/h), \quad (5.1)$$

where I_0 is the (extrapolated) central surface brightness and h is the radial *scale length* of the disk. Such a law produces a straight line on a plot of surface brightness in magnitudes per arc-sec² versus radius, since $\log I(R)$ falls as a linear function of R . At small radii, the luminosity profile may deviate either above or below an exponential law; the former are known as ‘Type I’ profiles, the latter as ‘Type II’ (Freeman 1970). At large radii, galactic disks often appear to be truncated; the surface brightness falls rapidly toward zero beyond $R > r_{\text{trun}} \simeq (4.2 \pm 0.6)h$ (van der Kruit & Searle 1982).

Studies of edge-on disk galaxies show that most of the luminosity comes from a rather thin component. Optical observations, although compromised by dust close to the midplane, suggest the distribution perpendicular to the disk is reasonably well-fit by the $\text{sech}^2(z)$ profile of a self-gravitating sheet with Gaussian velocity dispersion independent of z ; moreover, the vertical scale height appears to be independent of radius (van der Kruit & Searle 1981a,b). Combining these results leads to a widely-used fitting function for the 3-D luminosity distribution of galactic disks:

$$j(r,z) = \begin{cases} j_0 \exp(-r/h) \text{sech}^2(z/2z_0), & r < r_{\text{trun}} \\ 0, & \text{otherwise} \end{cases} \quad (5.2)$$

where j_0 is the in-plane luminosity density at the center of the disk, h is the radial scale length, and z_0 is the vertical scale height. While the *vertical* fitting function has a simple theoretical interpre-

tation, the *radial* function is strictly empirical, and only tested over a rather small range of surface brightness.

On the other hand, near-IR observations reveal more steeply peaked luminosity profiles near $z \sim 0$ (Wainscoat, Freeman, & Hyland 1989); the data fit a profile of the form $e^{-|z|}$. The corresponding 3-D luminosity distribution is

$$j(r, z) = \begin{cases} j_0 \exp(-r/h) \exp(-|z|/z_0), & r < r_{\text{trun}} \\ 0, & \text{otherwise} \end{cases} \quad (5.3)$$

where j_0 , h , and z_0 have the same definitions as above. Note that (5.2) and (5.3) asymptotically approach each other for $|z| \gg z_0$.

When the exponential luminosity profiles of typical disk galaxies are extrapolated to the very center, the range of central surface brightness values obtained is remarkably small; the ‘magic’ number is $21.65 \pm 0.3 \text{ mag arcsec}^{-2}$ in the B band (Freeman 1970). However, this result is largely a selection effect: disk galaxies with lower surface brightnesses are not easily detected (Disney 1976, MB81, Bothun, Impey, & McGaugh 1997). Moreover, some of the light attributed to disks may in fact come from spheroidal components (Kormendy 1977, K82).

Some edge-on disk galaxies appear to have ‘thick disks’ (Burstein 1979); these are components with flattenings intermediate between the disk and bulge which remain when a luminosity model following (5.2) is subtracted from the photometry (van der Kruit & Searle 1981a,b, 1982). In the Milky Way, we have good kinematic evidence that the thick disk of our galaxy is rotating and therefore actually deserves to be called a disk. Comparable evidence is not yet available for other galaxies, and some authors interpret thick disks as more closely associated with bulges or halos.

The colors of galactic disks do not display the systematic trends with radius and total luminosity seen in elliptical galaxies (Wevers et al. 1986). In general, spiral galaxies become somewhat more blue with increasing radius (see BM98, fig. 4.54 for an example), but this probably reflects the decreasing contribution of bulges at large R .

5.1.2 Bulge luminosity distribution

In galaxies such as NGC 4594, with bulges which dominate the total light distribution, the morphological resemblance between bulges and elliptical galaxies is quite close; such bulges have luminosity profiles reasonably well-approximated by de Vaucouleurs’ law (4.1).

In galaxies with more substantial disks the bulge component is often identified with whatever is left when the disk is subtracted from the surface photometry (by this definition, the thick disk is part of the bulge, a point of view endorsed by K82). This residual component may or may not follow de Vaucouleurs’ law.

The isophote shapes of bulges provide evidence that at least some of these objects are not simply ellipticals which have acquired disks. Bulges of edge-on galaxies are often quite ‘boxy’, and in some cases these isophotal distortions are so extreme that the bulge appears ‘peanut-shaped’ (e.g. NGC 128).

Bulge colors are generally similar to those of elliptical galaxies of the same luminosity, and to the extent that color gradients can be measured in the presence of a disk, bulges show radial color gradients similar to those of ellipticals (Wirth & Shaw 1983; Gilmore, King, & van der Kruit 1989, hereafter GKvdK89, Chapter 5.3).

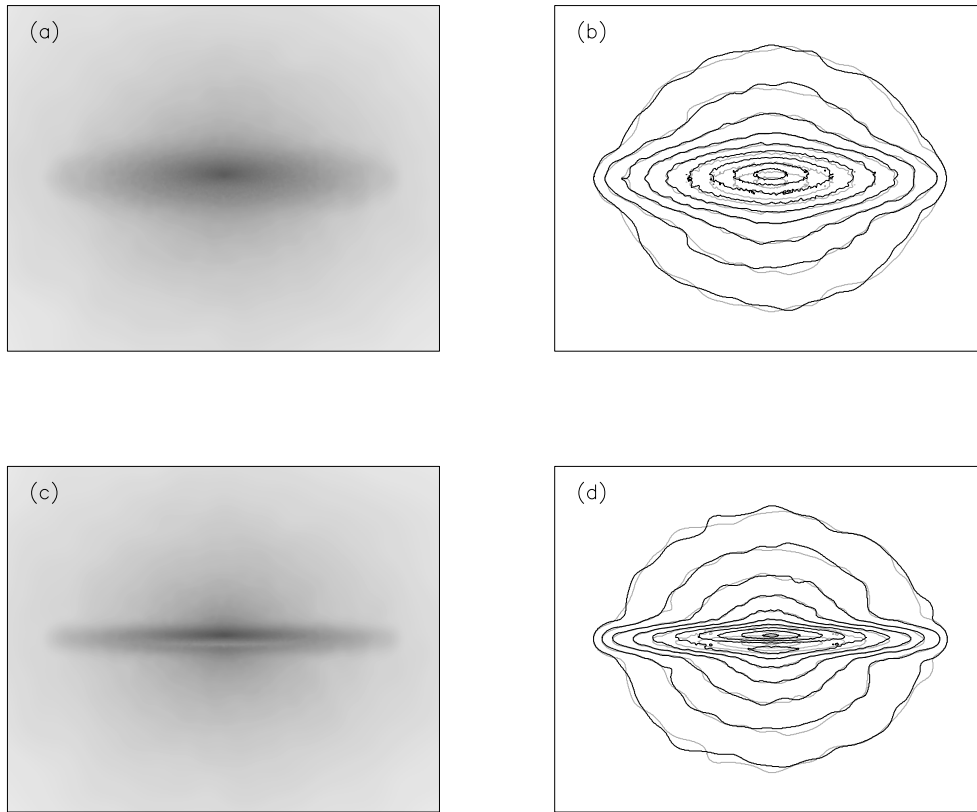


Figure 5.1: Model of a dusty disk galaxy. The disk contains 87.5% of the light, and both the stellar disk and bulge have the same projected half-light radius when viewed face-on; the scale length of the dust disk is 1.5 times that of the stellar disk. Viewed face-on, the extinction through the center of the dust disk is about 4 magnitudes. The disk is viewed nearly edge-on, with its bottom half nearer to us. (a) Half-tone image 15° from edge-on. (b) Isophotes of (a); the light grey contours show the result of flipping the image about the horizontal axis. (c) Like (a), but 5° from edge-on. (d) Isophotes of (c).

5.1.3 Dust

Glancing through the *Hubble Atlas*, it's evident that late-type (Sb & Sc) galaxies contain a good deal of dust. This material is most striking when galaxies are viewed edge-on, producing a narrow dust lane which bisects the disk. In nearly edge-on galaxies, the general effect is to dim the *near* side of the disk, as shown in Fig. 5.1. Notice that the isophotes near the center are displaced toward the far side of the disk.

Efforts to quantify the extinction due to this gunk have been controversial. Holmberg (1975) noted that an optically thick galaxy will appear fainter when viewed edge-on; analyzing surface photometry data for a large sample of late-type spirals, Valentijn (1990) claimed that galaxies are highly opaque, with optical depths greater than unity even when viewed face-on. Huizinga & van Albada (1992) reanalyzed the same data and concluded that extinction effects are much less ex-

treme; ‘the central regions [of Sc galaxies] are essentially opaque, and the outer regions nearly fully transparent’. A more recent study, comparing galaxies in B and in K , also finds that the central regions of Sb and Sc galaxies are opaque, with optical depths in B of $\tau = 1.0$ to 2.0 , but their outskirts are nearly transparent, with $\tau = 0.1$ to 0.5 at the isophote corresponding to $25 \text{ mag arcsec}^{-2}$ in B (Peletier et al. 1995).

The extinction in our own galaxy has been estimated by a variety of techniques. Hubble (1936) fit number-counts of external galaxies as a function of galactic latitude b to a model in which the dust lies in a slab of uniform thickness, producing extinction which varies as $A \propto \csc(b)$. Burstein & Heiles (1982) combined galaxy counts with neutral hydrogen data to produce maps of extinction for $|b| > 10^\circ$. Such maps are useful in correcting photometry of extragalactic objects for galactic extinction. Finally, Schlegel, Finkbeiner, & Davis (1998) used *COBE* and *IRAS* data to make maps of dust temperature and FIR emission; these maps are then combined to yield the dust column along each line of sight. The maps reveal a complex distribution of dust reminiscent of terrestrial cirrus clouds (hence the term ‘galactic cirrus’).

Is our own galaxy opaque? According to Schlegel et al. (1998), the B -band extinctions to the north and south galactic poles are 0.065 mag and 0.080 mag , respectively. The total extinction for a line of sight passing perpendicularly through the disk at the Sun’s position is then $\sim 0.145 \text{ mag}$, corresponding to an optical depth of $\tau \simeq 0.13$. This is certainly at the low end of the range of opacities reported by Peletier et al. (1995); it’s interesting to speculate how extragalactic astronomy might have developed if we lived in a highly opaque part of the Milky Way!

5.1.4 Gas

Interstellar gas is conspicuous in disk galaxies of type Sa and later. In the optical, most of this material is seen in a layer with a scale height significantly smaller than that of the stellar disk. 21 cm observations reveal extended gas disks surrounding the optical outlines of spiral and irregular galaxies.

HI studies of the Milky Way reveal a population of ‘high-velocity clouds’ (HVCs), so-called because they do not follow the relationship between galactic longitude and radial velocity for gas in the MW’s disk. The interpretation of these HVCs is ambiguous because we don’t know their distances; they may be close, in which case they represent relatively little mass, or distant and more massive.

The radial distribution of gas in disk galaxies seldom follows the exponential distribution seen in the starlight. Neutral hydrogen profiles for disk galaxies have a wide range of forms; the gas generally extends far beyond the stellar disk, while some galaxies have central holes in HI.

Molecular gas, detected via transitions of CO, tends to be more concentrated toward the centers of galaxies, often in the form of rings of dense gas. CO emission is correlated with spiral arms and regions of ongoing star formation. Estimates of the total mass of molecular material are somewhat uncertain since a conversion factor must be applied to relate CO emission to H_2 mass.

On the whole, late-type spirals are more gas rich than earlier types; the median ratio of gas to total mass increases by nearly an order of magnitude from Sa galaxies to Scd galaxies. Somewhat paradoxically, however, early-type galaxies appear to have larger fractions of molecular gas, while late-type systems are dominated by atomic gas (Young & Scoville 1991).

5.1.5 Decompositions

To the extent that bulges and disks follow fitting functions such as (5.2) and (4.1) one can attempt to model the surface-brightness distribution of a galaxy and thereby determine the parameters of the individual components. This game is probably best played using red or near-IR images to reduce the sensitivity to dust and ongoing star formation. AS MB98 (§ 4.4.3) note, such *decompositions* are more reliable when fit to two-dimensional surface photometry; older studies based on major-axis luminosity profiles are probably subject to systematic uncertainties.

Decomposing a galaxy into separate bulge and disk components is always a bit uncertain, since some bulges and disks don't follow (5.2) and (4.1). Does the residual light left over after the disk and bulge are subtracted represent additional components, or is it simply the result of a poor choice of fitting functions? Surface photometry in a single waveband is probably inadequate to address this question; color and/or kinematic information may help resolve the issue.

5.2 Structures

5.2.1 Spirals

Disk galaxies exhibit a wide variety of spiral structure, a point explicitly recognized in de Vaucouleurs' classification system. 'Grand design' spirals have rather regular patterns dominated by a pair of symmetrically-placed spiral arms. Such spirals are often found in galaxies with close companions (e.g. M51); they may be the result of tidal interactions. 'Flocculent' spirals have many short spiral arms, with no overall pattern (e.g. NGC 2841).

The angle ψ between the ridge-line of a spiral arm and a tangent to a circle of constant galactocentric radius is known as the arm's *pitch angle*. According to Hubble's classification system (§ 3.1.1), Sa galaxies have tightly-wound spirals, while Sc galaxies are loosely-wound. Indeed, Sa galaxies have pitch angles $\psi \simeq 5^\circ$, while Sc galaxies have $\psi \simeq 10^\circ$ to 30° . If ψ is independent of radius then the arm traces a *logarithmic spiral*, defined by

$$\ln(R) = \tan(\psi)\phi + \text{const.} \quad (5.4)$$

in polar coordinates (R, ϕ) .

Spiral arms are often sites of star formation. In such disks azimuthal color variations are closely connected to the spiral pattern, with hot young stars and emission nebulae distributed along the ridge-lines of spiral arms (e.g. NGC 2997, shown on the cover of BT87). However, near-IR observations indicate that in many cases the older stars also follow a spiral pattern.

Whatever the type of spiral, the overall quality of structure is closely correlated with a galaxy's luminosity; bright disk galaxies tend to have rather neat and well-developed spiral patterns, while fainter galaxies look messier, and for low-luminosity systems the distinction between spiral and irregular galaxies becomes irrelevant.

5.2.2 Bars

A large fraction of disk galaxies have *bars*: narrow linear structures crossing the face of the galaxy. In barred S0 galaxies the bar is often the only structure visible in the disk. In types Sa and later the bar often connects to a spiral pattern extending to larger radii (e.g. NGC 1300).

Viewed face-on, bars typically appear to have axial ratios $a/b > 2$. The surface brightness within the bar is often fairly constant. Some bars appear to be ‘squared off’ at the ends. The true 3-D shapes of bars are difficult to determine, but many appear to be no thicker than the disks they occur in; if so then bars are the most flattened triaxial systems known (K82).

Bars in edge-on galaxies are hard to detect photometrically; however, kinematic signatures of barred potentials have been used to infer their presence in some edge-on systems. What is noteworthy is that such edge-on bars appear to be associated with boxy or peanut-shaped bulges. This association suggests that such bulges are in fact *produced* by the evolution of galactic bars, possibly via a dynamical instability acting on thin stellar bars.

5.2.3 Rings & lenses

Many barred galaxies also contain luminous *rings*. Most striking are those in which the ring just encloses the bar (e.g. NGC 2523); these are known as *inner* rings and are designated by appending the symbol ‘(r)’ to the morphological type. Less common are *outer* rings, which typically have diameters several times that of the bar (e.g. NGC 1291; see K82); these are designated with the symbol ‘(R)’. Inner rings often appear to be elongated in the direction of the bar, while outer rings seem to be more nearly circular.

In some cases the region inside the inner ring is more or less uniformly filled in with luminosity; these luminous oval structures are called *lenses*. Like bars, lenses have very shallow radial luminosity gradients. The close association between bars, inner rings, and lenses suggests an evolutionary connection (K82).

5.2.4 Warps

The same observations which establish the presence of dark halos also show that the outer regions of disk galaxies are often warped. In edge-on galaxies such as NGC 5907 such warps are seen as so-called ‘integral sign’ contours bending symmetrically away from the plane of the disk (e.g. MB81, Fig. 8-30). In disks seen more nearly face-on warps are revealed by characteristic distortions of the iso-velocity contours (MB81, Fig. 8-27) such that the kinematic principal axes remain roughly perpendicular at all radii. Such distorted velocity maps can be modeled by treating the disk as a collection of concentric circular rings, each tilted by a small amount with respect to its neighbors (MB81, Fig. 8-28).

Warps are very common. For example, the Milky Way, M31, and M33 are all warped (e.g. Binney 1992); the warp of M33 is so strong that some lines of sight intersect the disk more than once (MB81, Fig. 8-29).

Unlike the spirals of disk galaxies, which occur in a profusion of forms, galactic warps obey some fairly simple rules (Briggs 1990):

- the warp develops between R_{25} , where the B surface brightness is $25 \text{ mag arcsec}^{-2}$, and $R_{26.5}$ (a.k.a. the Holmberg radius);
- the line of nodes is approximately straight within $R_{26.5}$;
- the line of nodes takes the form of a loose *leading* spiral beyond $R_{26.5}$.

5.3 Star Formation

The integrated colors of disk galaxies reveal trends with morphological type; S0 and Sa galaxies are red, while Sc and Sd galaxies are blue. These trends reflect different rates of star formation; broadband colors are sensitive to the average star formation rate over the last 10^8 years (Tinsley 1980). On a ‘color-color plot’ (for example, a plot with $(B - V)$ on one axis and $(U - B)$ on the other), galaxies scatter along a 1-dimensional sequence. Stellar population synthesis models suggest that the parameter determining a galaxy’s position along this sequence is the ratio of its present star formation rate to the average rate over the galaxy’s lifetime, $b \equiv \text{SFR}/\langle\text{SFR}\rangle$. Along the Hubble sequence, median values of b range from < 0.07 in Sa galaxies to ~ 1.0 in Sc galaxies (Kennicutt, Tamblyn, & Congdon 1994).

Ongoing star formation may be quantified by measuring the flux in the $H\alpha$ spectral line. The basic idea here is to use the $H\alpha$ line as a proxy for the ionizing radiation emitted by young stars. This assumes that little of this radiation escapes directly or is absorbed by dust – an assumption which can now be checked by direct observation (e.g., Gordon et al. 2004). Although dust does absorb and re-emit a significant amount of radiation, equivalent widths of the $H\alpha$ line are strongly correlated with morphological type.

Studies of star formation in normal and starburst galaxies yield a power-law relationship between star formation per unit surface area, $\dot{\Sigma}_*$, and gas surface density, Σ_g :

$$\dot{\Sigma}_* \simeq (2.5 \pm 0.7) \times 10^{-4} \frac{M_\odot}{\text{yrkpc}^2} \left(\frac{\Sigma_g}{1M_\odot\text{pc}^{-2}} \right)^{1.4 \pm 0.15}. \quad (5.5)$$

extending over nearly 5 orders of magnitude in Σ_g (Kennicutt 1988). A relationship of this kind was first proposed by Schmidt (1959), and (5.5) is sometimes known as the Schmidt law. Nonetheless, the observed spread in $\dot{\Sigma}_*$ at a given Σ_g is as much as a factor of 10; it seems more appropriate to call (5.5) a ‘suggestion’ rather than a law.

5.4 Kinematics

That disk galaxies rotate is fairly obvious from their spiral patterns. Early observations could only reveal the rotation curves of the brightest inner regions; these typically show a fairly rapid increase with radius before leveling off. Assuming that rotation velocities dropped as $v(r)$ proportional to $r^{-1/2}$ at larger radii, astronomers derived total masses for spiral galaxies comparable to the masses of the visible stars.

Improved observations, however, failed to show the expected Keplerian fall-off in rotation velocity. Optical studies showed rotation curves remaining nearly constant out to the last measurable point at a radius of 4 or 5 h (Rubin 1983). Neutral hydrogen observations generally confirmed these results and in some cases extended them to radii several times greater still (e.g. van Albada et al. 1985). Larger samples showed that ‘flat’ rotation curves are not always the norm; dwarf galaxies usually have *rising* rotation curves, while luminous spirals, particularly those with relatively compact disks, often have gently *falling* rotation curves (Casertano & van Gorkom 1991). Nonetheless, *a Keplerian rotation profile has not been observed in any galaxy*. Consequently, we do not know the total mass of any disk galaxy.

The above results refer to the gas, because emission lines are relatively easy to observe. What about the disk stars? In practice, the stellar distribution rotates slightly slower than the gas (e.g. GKvdK89, Fig. 10.5). As will be shown, this difference is due to the velocity dispersion of the stellar component.

But a surprising result emerges when velocity distributions are examined in detail: a few disk galaxies contain significant *counterrotating* components! For example, the S0 galaxy NGC 128 has a counterrotating inclined nuclear gas disk (Emsellem & Arsenault 1997). The Sab galaxy NGC 4826 has *two* nested gas disks; the outer one rotates with the stars, while the inner one rotates in the opposite direction (Braun et al. 1994). The disk of the E7/S0 galaxy NGC 4550 contains nearly equal numbers of stars rotating in each direction (Rubin, Graham, & Kenney 1992; Rix et al. 1992). In the Sab galaxy NGC 7217 the counterrotating fraction is smaller, amounting to about 30% of the disk stars (Merrifield & Kuijken 1994); counterrotating fractions of this order could exist in many disk galaxies, though no counterrotating *disk* stars are known in the Milky Way.

The kinematics of bulges are, to first order, similar to the kinematics of elliptical galaxies of the same luminosity; both bulges and low-luminosity ellipticals rotate fast enough to explain their observed flattenings. Unlike some elliptical galaxies, bulges generally have well-aligned rotation and minor axes. In normal bulges, rotation velocity decreases smoothly with increasing height above the disk. Boxy or peanut-shaped bulges, on the other hand, appear to rotate rapidly even well above the disk plane (e.g. K82).

5.4.1 Parameter correlations

Like elliptical galaxies, spirals obey a number of different parameter correlations. An important example is the *Tully-Fisher* relation (Tully & Fisher 1977), a correlation between the rotation velocities and total luminosities of disk galaxies.

Because disk galaxies have essentially flat rotation curves, the integrated neutral hydrogen line profile of an inclined disk galaxy displays a characteristic ‘double horned’ morphology. The width of such a line profile, corrected for galaxy inclination, provides a measure of the peak-to-peak amplitude of the rotation curve. In the published form of the TF relation (e.g. Pierce & Tully 1992, Tully & Pierce 2000), the inclination-corrected line width W is related to the total luminosity L by a power law,

$$L \propto W^n, \quad (5.6)$$

where the index n had a value close to 4. This is very similar to the Faber-Jackson relation for elliptical galaxies, which states that luminosity scales as the fourth power of the central velocity dispersion. No good theoretical explanation for these laws is yet available; the rotation curve amplitude of a disk galaxy is presumably set by its invisible halo, and it is not obvious why the halo parameters are so nicely correlated with the total luminosity. Nonetheless, the TF relation is very useful for measuring distances to disk galaxies.