

GALACTIC MORPHOLOGY & STRUCTURE

A. Elliptical Galaxies. Most galaxies can be readily decomposed into two main structural components, disk and bulge. Elliptical galaxies are all bulge. The radial brightness profile of the bulge component is usually parameterized by one of three laws. The earliest and simplest is an empirical relation called the Hubble law,

$$\mu(r) = \mu_o(1 + r/r_o)^{-2} \quad ,$$

and is parametrized in terms of a central surface brightness, μ_o , and a scale length, r_o , at which the brightness falls to half its central value. At large radius, the profiles are falling as $1/r^2$. At radii less than the scale length, the profile flattens to μ_o . Giant elliptical galaxies typically have $\mu_o \approx 16$ mag/arc-second². A better relation is the empirical $r^{1/4}$ law proposed by de Vaucouleurs

$$\mu(r) = \mu_e \exp[-7.67((r/r_e)^{1/4} - 1)] \quad ,$$

where r_e is the effective radius and corresponds to the radius that encloses 1/2 of the total integrated luminosity of the galaxy, and μ_e is the surface brightness at that radius, approximately 1/2000 of the central surface brightness. The third relation is semiempirical and was derived from dynamical models calculated by King to fit the brightness profiles of globular star clusters (see Stellar Structure and Evolution). These models can be parametrized as

$$\mu(r) = \mu_K [(1 + r^2/r_c^2)^{-1/2} - (1 + r_t^2/r_c^2)^{-1/2}]^2,$$

where r_c again represents the core radius where the surface brightness falls to ≈ 0.5 , r_t is the truncation or tidal radius beyond which the surface brightness rapidly decreases, and μ_K is approximately the central surface brightness. Isolated elliptical galaxies are best fit by models with $r_t/r_c \approx 100$ -200. Small elliptical galaxies residing in the gravitational potential wells of more luminous galaxies (like the dwarf neighbors of our own galaxy) are tidally stripped and have $r_t/r_c \approx 10$. Figure 3 shows examples of the Hubble and de Vaucouleurs laws and the King models.

Dwarf elliptical galaxies, designated dE, are low luminosity, very low surface brightness objects. Because of their low surface brightness, they are difficult to identify against the brightness of the night sky (airglow). The nearest dwarf elliptical galaxies, Ursa Minor, Draco, Sculptor and Fornax, are satellites of our own galaxy, and are resolved into individual stars with large telescopes. Although dE galaxies do not contribute significantly to the total luminosity of our own Local Group of galaxies, they dominate its numbers (Table 2). As mentioned above, dwarf galaxies are often tidally truncated by the gravitational field of neighboring massive galaxies. If M is the mass of the large galaxy, m is the mass of the dwarf, and R is their separation, then the tidal radius, r_t , is given by

$$r_t = R \left(\frac{m}{3M} \right)^{1/3} \quad .$$

Frequently the central brightest galaxy in a galaxy cluster exhibits a visibly extended halo to large radii. These objects were first noted by W. W. Morgan and

are designated “cD” galaxies in his classification scheme. Unlike ordinary giant E galaxies, whose brightness profiles exhibit the truncation characteristic of de Vaucouleurs or King profiles at radii of 50 to 100 kpc, cD galaxies have profiles which fall as $1/r^2$ or shallower to radii in excess of 100 kpc. “D” galaxies are slightly less luminous and have weaker halos; D galaxies are found at maxima in the density distribution of galaxies. The extended halos of these objects are considered to be the result of dynamical processes that occur either during the formation or subsequent evolution of galaxies in dense regions.

The internal dynamics of spheroidal systems (E galaxies and the bulges of spirals) is understood in terms of a self gravitating, essentially collisionless gas of stars. These systems appear dynamically relaxed; they are basically in thermodynamic equilibrium as isothermal spheres with Maxwellian velocity distributions. Faber and Jackson noted in 1976 that the luminosities of E galaxies were well correlated with their internal velocity dispersions.

$$L \approx \sigma^4 \quad .$$

Here, the velocity dispersion, σ , is a measure of the random velocities of stars along the line-of-sight.

The collisional or two-body relaxation time, t_r , for stars is approximately

$$t_r \sim 2 \times 10^8 \frac{V^3}{M^2 \rho} \text{ years} \quad ,$$

where V is the mean velocity in km s^{-1} , ρ is the density of stars per cubic parsec and M is the mean stellar mass in M_\odot . This relaxation time in galaxies is 10^{14} to 10^{18} years — much longer than the age of the universe. Two-body relaxation is generally not important in the internal dynamics of galaxies, but is significant in globular clusters.

The relaxed appearance of galactic spheroids is probably due to the process called violent relaxation. This is a statistical mechanical process described by Lynden-Bell, where individual stars primarily feel the mean gravitational potential of the system. If this potential fluctuates rapidly with time, as in the initial collapse of a galaxy, then the energy of *individual* stars is not conserved. The results of numerical experiments are similar to galaxy spheroids.

For the last decade and a half, the determination and modeling of the true shapes of elliptical galaxies has been a major problem in galaxian dynamics. Most elliptical galaxies are somewhat flattened. Early workers assumed that this flattening was rotationally supported as in disk galaxies (see below). Bertola and others observed, however, that the rotational velocities of E galaxies are insufficient to support their shapes (Figure 5). The velocity dispersion is a measure of the random kinetic energy in the system.

To resolve this problem, Binney, Schwarzschild and others suggested that E galaxies might be prolate (cigar shaped) or even triaxial systems instead of oblate

(disklike) spheroids. Current work favors the view that most flattened elliptical galaxies are triaxial and have internal stellar velocity distributions which are anisotropic. A small fraction do rotate fast enough to support their shapes.

B. S0 Galaxies. Spiral and S0 galaxies can be decomposed into two surface brightness components, the bulge and disk. Disks have brightness profiles that fall exponentially

$$\mu(r) = \mu_0 \exp(-r/r_s) \quad .$$

Bulges have been described above. Disks are rotating; their rotational velocity at any radius is presumed to balance the gravitational attraction of the material inside. A typical rotation curve (velocity of rotation as a function of radius) is shown in Figure 6.

Disks are not infinitely thin. The thickness of the disk depends on the balance between the surface mass density in the disk (gravitational potential) and the kinetic energy in motion perpendicular to the disk. This can be a function of both the initial formation of the system and its later interaction with other galaxies, etc. Tidal interaction with other galaxies will “puff up” a galactic disk of stars. Disks of S0 galaxies are composed of old stars and do not exhibit any indications of recent star formation and associated gas or dust - that is part of the definition of an S0.

Bulges of S0 galaxies and spirals **do** rotate and appear to be simply rotationally flattened oblate spheroids. We will return to this point later when we discuss galaxy formation.

C. Spiral Galaxies. Unlike the smooth and uncomplicated disks of S0 galaxies, the disks of spiral galaxies generally exhibit significant amounts of interstellar gas and dust and distinct spiral patterns. The disk rotates differentially (see Figure 6) and the spiral pattern traces the distribution of recent star formation in the galaxy. Regions of recent star formation have a higher surface brightness than the background disk. Although the spiral is a result of the rotation of the material in the disk, the pattern need not (and generally does not) rotate with the same speed as the material.

The rotation of a spiral galaxy can be described in terms of a velocity rotation curve, $v(r)$, or the angular rotation rate, $\Omega(r)$, where $v = r\Omega$. In 1927, Oort first measured the local differential rotation of our galaxy by studying the motions of nearby stars. He described that rotation in terms of two constants, now known as Oort’s Constants, which are measures of the local shear (A) and vorticity (B) :

$$A = -\frac{r}{2} \frac{d\Omega}{dr} \quad , \quad B = -\frac{1}{2r} \frac{d}{dr}(r^2\Omega) \quad .$$

The values adopted by the IAU (International Astronomical Union) in 1964 are $A = 15 \text{ km s}^{-1} \text{ kpc}^{-1}$ and $B = -10 \text{ km s}^{-1} \text{ kpc}^{-1}$, with the Sun at a distance of $r_o = 10 \text{ kpc}$ from the center of the galaxy, and the rotation rate at the sun $V_{\odot} = 250 \text{ km s}^{-1}$. Current estimates support a smaller Sun-Galactic-center distance ($\sim 8 \text{ kpc}$) and a smaller rotation velocity ($\sim 230 \text{ km s}^{-1}$) as well as slightly different values for A and B.

Studies of rotation in spiral galaxies are undertaken by long-slit spectroscopy at different position angles in the optical or by either integrated (total intensity, big beam) measurements or interferometric mapping in the 21-cm line of neutral hydrogen. The neutral hydrogen (HI) in spiral galaxies is primarily found outside their central regions, reaching a maximum in surface density several kiloparsecs from the center. The gas at the center is mostly in the form of molecular hydrogen, H₂, as deduced from carbon monoxide (CO) maps. From such detailed studies by Rubin, Roberts and others we know that the rotation curves for spirals generally rise very steeply within a few kiloparsecs of their centers then flatten and stay at an almost constant velocity as far as they can be measured. This result is rather startling because the luminosity in galaxies is falling rapidly at large radii. If the light and mass were distributed similarly, then the rotational velocity should fall off as $1/R$ at large radii as predicted by Kepler's laws. Only a small number of galaxies show the expected Keplerian falloff, leading to the conclusion that the mass in spiral galaxies is **not** distributed as the light.

As in elliptical galaxies, Fisher and Tully noted in 1976 that the luminosities of spiral galaxies are correlated with their internal motions, in particular rotational velocity. The best form of this relation is seen in the near infrared where the effects of internal extinction by dust on the luminosities are minimized (Figure 7). There the relation is approximately

$$L = (\Delta V)^4 \quad ,$$

where ΔV is the full width of the HI profile measured at either 20% or 50% of the peak. As the HI distribution peaks outside the region where the rotational velocity has flattened, the HI profile is sharp sided and is double peaked for galaxies inclined to the line of sight.

The regularity of the spiral structure seen in these galaxies is exceptional. If the spiral pattern was merely tied to the matter distribution, differential rotation would 'erase' it in a few rotation periods. A typical rotation time is a few hundred million years, or $\approx 1/100$ th the age of the universe. To explain the persistence of spiral structure, Lin and Shu introduced the Density Wave theory in 1964. In this model, the spiral pattern is the star formation produced in a shock wave induced by a density wave propagating in the galaxy disk. The spiral pattern is in solid body rotation with a pattern speed Ω_p . The main features of such a density wave are the corotation radius, where the pattern and rotation angular speeds are the same, and the inner and outer Lindblad resonances, where

$$\Omega_p = \Omega \pm \kappa/m \quad ;$$

m is the mode of oscillation and κ is the epicyclic frequency in the disk,

$$\kappa^2 = r^{-3} \frac{d(r^4 \Omega^2)}{dr} \quad ,$$

or

$$\kappa = \frac{2\Omega}{(1 - A/B)^{1/2}} \quad .$$

Figure 8 depicts the features of a density wave. The spiral pattern only exists between the Lindblad resonances. Galaxies in which a single mode dominates are called “Grand Design” spirals.

Two alternative models have been proposed to account for spiral patterns, the Stochastic Star Formation (SSF) model of Seiden and Gerola, and the tidal encounter model. In the first, regions of star formation induce star formation in neighboring regions. With proper adjustment of the rotation and propagation timescales, reasonable spiral patterns result. In the second, spiral structure is the result of galaxy interactions. A possible example of this process is shown in Figure 9. It is likely that all three processes operate in nature, with density waves producing the most regular spirals, SSF producing ‘flocculent’ spirals, and tidal encounter model. In the first, regions of star formation induce star formation in neighboring regions. With proper adjustment of the rotation and propagation timescales, reasonable spiral patterns result. In the second, spiral structure is the result of galaxy interactions. A possible example of this process is shown in Figure 9. It is likely that all three processes operate in nature, with density waves producing the most regular spirals, SSF producing ‘flocculent’ spirals, and tidal interactions producing systems like the Whirlpool. A significant fraction ($\sim 10\%$) of all galaxies show some form of interaction with their neighbors. Not all such systems contain spiral galaxies, however.

D. Irregular Galaxies. Galaxies are classified as Irregular for several different reasons. In the morphological progression of the Hubble sequence the true Irregulars are the Magellanic Irregulars, the Irr I’s, which are galaxies with no developed spiral structure that are usually dominated by large numbers of star forming regions. Irregular II’s and other peculiar objects have been extensively cataloged by Arp and his coworkers, by Vorontsov-Velyaminov and by Zwicky. These objects are usually given labels to describe their peculiar properties such as ‘compact,’ which usually indicates abnormally high surface brightness or a very steep brightness profile, ‘post-eruptive,’ which usually indicates the existents of jets or filaments of material near the galaxy, ‘interacting,’ or ‘patchy.’ There are also galaxies in the form of rings which are thought to be produced by a slow, head-on collision of two galaxies, one of which must be a gas rich spiral. The collision removes the nucleus of the spiral leaving a nearly round ripple of star formation similar to the ripples produced when a rock is dropped into a lake. Such ring galaxies almost always have compact companion galaxies which are the likely culprits.

The Magellanic irregulars are almost always dwarf galaxies (low luminosity), are very rich in neutral hydrogen and have relatively young stellar populations. Their internal kinematics may show evidence for regular structure or may be chaotic in nature. These galaxies are generally of low mass; the largest such systems have internal velocity dispersions (usually measured by the width of their 21-cm Hydrogen line) less than 100 km s^{-1} . Their detailed internal dynamics have only been poorly studied up until now. There are some indications that star formation proceeds in these galaxies as in the SSF theory mentioned above, however evidence also exists for H II regions aligned with possible shock fronts. Although they do not contribute

significantly to the total luminosity density of the universe, these galaxies and the dwarf ellipticals dominate the total number of galaxies.

More on Galaxy “Shapes”

Since 1990 or so, there has been increased emphasis on actually predicting the mass profiles for galaxies either from simple first principles or more empirically from N-body simulations of galaxy formation. One of the first of such “density” profiles is the:

Hernquist Profile (Hernquist 1990)

$$\rho(r) \propto \frac{1}{r(1+r/r_s)^3}$$

On larger scales, there have also been density profiles put forward for clusters of galaxies such as the:

Navarro Profile (Navarro 1995) for x-ray halos

$$\rho(r) \propto \frac{1}{r(1+r/r_s)^2}$$

Note that these are *DENSITY* profiles and not *Surface Brightness* profiles, so comparison with observed galaxy profiles such as the above deVaucoulerus Law requires conversion from 3-D to projected 2-D.

The most recent, and at some level controversial, profiles are surface brightness profile from the HST Key Project on galaxy central dynamics (done by a group of people collectively known as the “Nukers” for their work on galactic black holes):

The “Nuker” Law

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{r}{r_b}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_b}\right)^\alpha\right]^{(\gamma-\beta)/\alpha}$$

Where I_b is the intensity at the core radius, also known as the break radius, r_b , is I_b , the inner power law slope is γ and the outer power law slope is β .

And the now standard, empirical, CDM predicted:

NFW Profile (Navarro, Frenk and White 1996, ApJ 462, 563)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

where $r_s = r_{200}/c$ is a characteristic radius and $\rho_{crit} = 3H^2/8\pi G$ is the cosmological critical density, and δ_c and c are two dimensionless parameters. With this profile linked to the critical density, the mass of the halo is

$$M_{200} = 200\rho_{crit}(4\pi/3)r_{200}^3$$

and the definition of r_{200} is that the mean density within r_{200} is $200\rho_{crit}$, such that

$$\delta_c = \frac{200}{3} \frac{c^3}{[\ln(1+c) - c/(1+c)]}$$

so that δ_c can be considered as the characteristic overdensity of the halo, r_s is its scale radius and c is its “concentration.”