Chapter 1

Introduction

1.1 What is a Galaxy?

It’s surprisingly difficult to answer the question “what is a galaxy?” Many astronomers seem content to say “I know one when I see one”. But one possible definition can be given:

> A galaxy is a *self-gravitating* system composed of an *interstellar medium*, *stars*, and *dark matter*.

It’s difficult to overstate the role of gravity in galaxies. While the electromagnetic force has the same r^{-2} dependence as gravity, charge cancellation insures that large-scale electromagnetic forces are relatively weak; in contrast, gravitational forces don’t cancel out since all forms of matter have the same “gravitational charge”. The structure and evolution of stars is governed by a delicate balance between gravity, radiation, and nuclear processes. The structure of a galaxy, on the other hand, is basically determined by gravity – other forces only enter indirectly.

The three key ingredients of galaxies – stars, interstellar matter, and dark matter – are usually present in different forms. Some of these forms are listed in Table 1.1. Not all of these components are found in every galaxy. In some galaxies, for example, star formation ended long ago, and no new stars have been born for many billions of years; in such galaxies the upper end of the main sequence is missing, as are the molecular clouds from which new stars are formed.

The key components of galaxies are not immutable – as galaxies evolve there may be a good deal of interchange between them. Hot and warm gas cool to form the cold clouds which give birth

Interstellar Medium	**Stars**	**Dark Matter**
molecular gas	main-sequence stars	stellar-mass black holes
dust	brown dwarfs	supermassive black holes
warm gas (10^4 K)	giant stars	stable neutral particles
hot gas (10^6 K)	supergiant stars	???
magnetic fields	white dwarf stars	
cosmic rays	neutron stars	

Table 1.1: Components of typical galaxies.

to stars. These stars return much of their mass, often enriched in “metals” – elements heavier than H and He – to the interstellar medium (ISM). Stellar evolution also yields remnants which add to the dark matter content, and both stars and gas may be accreted by black holes. Galaxies are sometimes described in terms like those used for ecological systems; while this analogy is inexact, it does capture some of the complex interchange of material in galactic systems.

The definition of a galaxy proposed above is flawed because it includes some objects which most people would agree are *not* galaxies. For example, a star cluster is a self-gravitating system composed of stars; is it therefore a galaxy? To be sure, most star clusters have little if any gas or dark matter; moreover, star clusters are generally found within galaxies. But denying star clusters the status of galaxies on such grounds seems somewhat arbitrary. Perhaps the best way to distinguish between star clusters and galaxies is to note that star clusters don’t exhibit much evidence of an interchange between components – all the stars in a cluster have the same age and metal content. If a galaxy may be likened to an ecological system, a star cluster is more like a monoculture grown in a petri dish.

1.2 Overview of the Milky Way

Key parameters for the Milky Way galaxy are listed in Table 1.2. These values illustrate some facts which are also true for many other galaxies. First, the MW’s disk is remarkably slender – indeed, the thin disk’s scale height is only $\sim 10\%$ of its scale radius. We will see that such thin disks can only survive in host galaxies with relatively quiescent gravitational potentials. Second, disk stars emit $\sim 80\%$ of the of the MW’s total luminosity. In other galaxies the disk-to-total ratio varies systematically with galaxy morphology, and the factors which determine this ratio are hotly debated. Third, the disk makes up no more than $\sim 15\%$ of the total *mass* within 35 kpc (Fich & Tremaine 1991); most of the MW’s mass has not been seen at any wavelength. The total mass of the MW is unknown.

Solar radius	R_0	$8.5 \pm 1\,\mathrm{kpc}$
Disk scale radius	R_d	$3.5 \pm 0.5\,\mathrm{kpc}$
Thin disk scale height		$350 \pm 50\,\mathrm{pc}$
Thick disk scale height		$1.25 \pm 0.25\,\mathrm{kpc}$
Disk luminosity	L_D	$1.2 \times 10^{10} L_\odot$
Bulge luminosity	L_B	$0.2 \times 10^{10} L_\odot$
Halo luminosity	L_H	$\leq 0.1 \times 10^{10} L_\odot$
Disk mass	M_D	$6 \times 10^{10} M_\odot$
Total mass	M_G	$\geq 4 \times 10^{11} M_\odot$

Table 1.2: Parameters of the Milky Way.

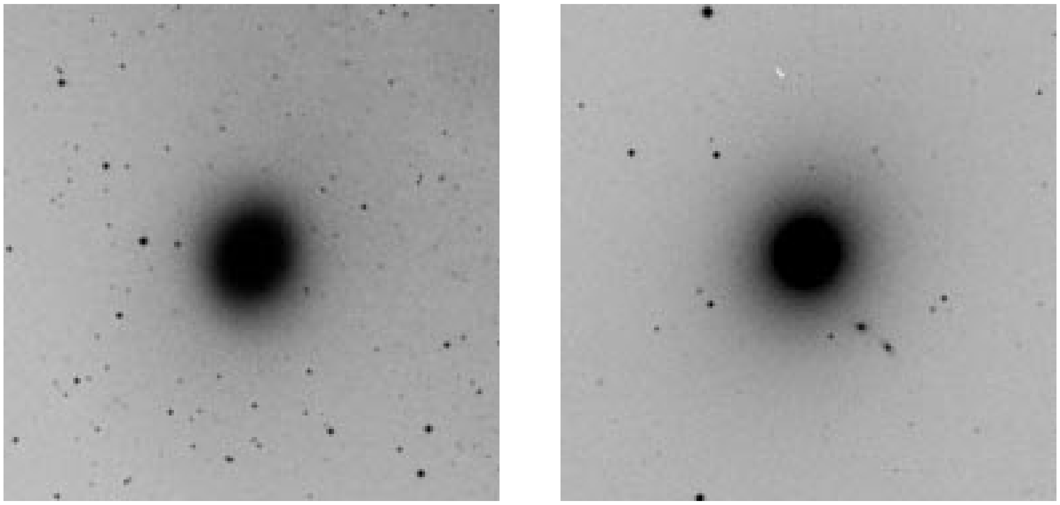

Figure 1.1: Two elliptical galaxies of similar apparent size and brightness. Both images are 10 × 10 arcmin. Source: Palomar digital sky survey.

1.3 Other Galaxies

1.3.1 Types

Most galaxies can be broadly classified into one of three general types:

- Disk galaxies generally resemble the Mikly Way; much of their luminosity is contained in thin, rotating disks of stars.
- Elliptical galaxies have nearly-featureless oval forms with approximately elliptical isophotes; rotation is not as important.
- Irregular/peculiar galaxies follow neither the disk nor elliptical plans; they lack apparent rotational symmetry.

These types were once thought to be fixed in the early stages of galaxy formation, but we now know that some peculiar galaxies are systems "in transition".

1.3.2 Sizes

Fig. 1.1 compares images of two well-known elliptical galaxies. These galaxies have similar apparent luminosities and angular sizes; one is a little more elongated than the other, but otherwise there seems not much difference between them. Fig. 1.2, a comparison taking relative distance into account, tells a very different story: one of the galaxies is a dwarf, the other a giant.

The resemblance of these two ellipticals shows that galaxies of very different sizes can be built on the same general pattern. Compare with stars; two stars with a similar ratio of masses ($\sim 500:1$) would occupy opposite extremes of the main sequence and *require* markedly different internal structures to maintain equilibrium. Freedom to rescale galaxy models in this manner comes about because gravitational dynamics is *scale-free*.

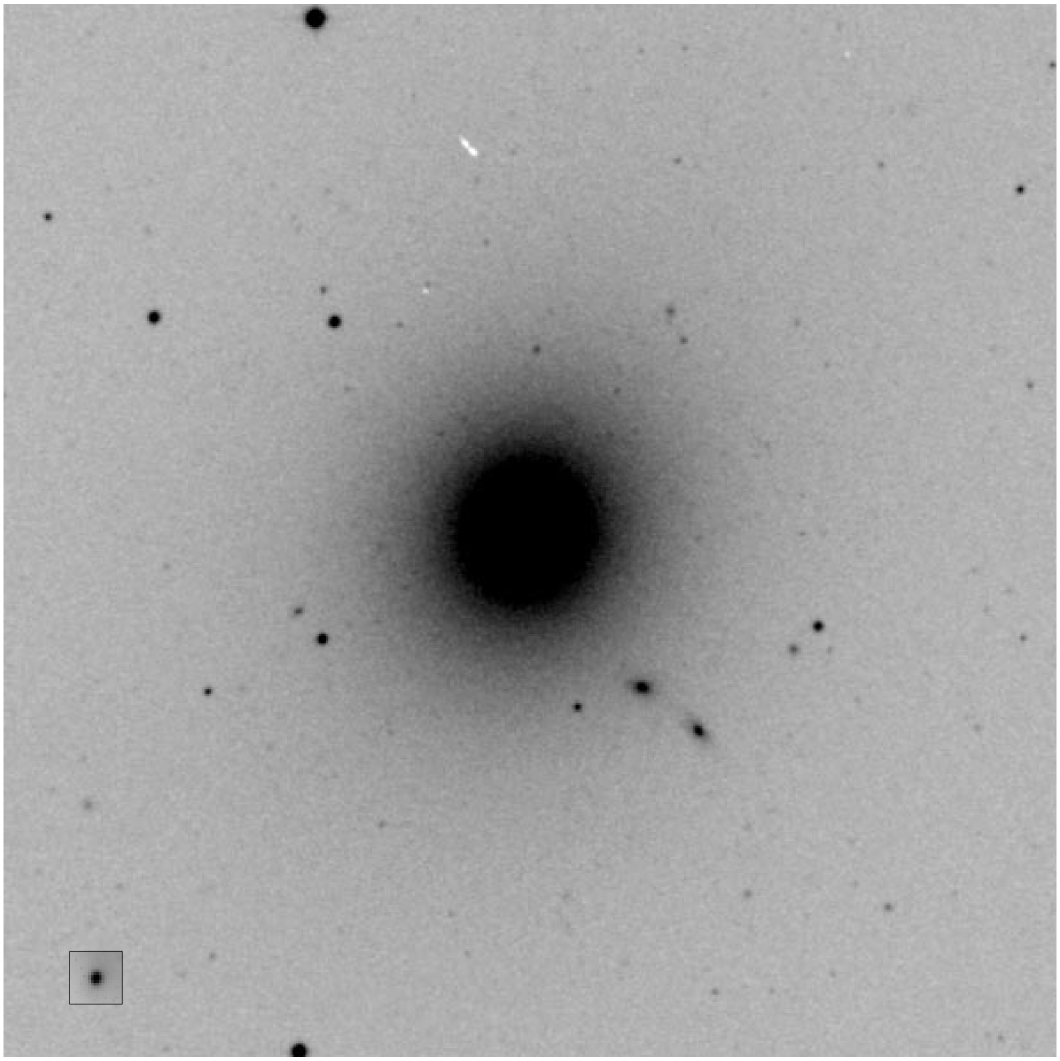

Figure 1.2: The two elliptical galaxies of the previous figure, now scaled to the same distance. The large galaxy is M87, a giant elliptical in the Virgo cluster, while the small one is M32, a dwarf elliptical satellite of the Andromeda galaxy. Source: Palomar digital sky survey.

1.3.3 Luminosity function

As Fig. 1.2 illustrates, galaxies span an enormous range of absolute luminosity. Empirically, the distribution of galaxy luminosities is well-fit by the Schecter function (Binney & Tremaine 1987, hereafter BT87, p. 21):

$$\phi(L) = \frac{n_\star}{L_\star}\left(\frac{L}{L_\star}\right)^{\alpha} e^{-L/L_\star}\,, \tag{1.1}$$

where $\phi(L)dL$ is the number of galaxies per unit volume with luminosities between L and $L + dL$. Here $n_\star \simeq 0.45 \times 10^{-2} h_{72}^{3}\,\mathrm{Mpc}^{-3}$ parameterizes the number density of galaxies, $L_\star \simeq 1.9 \times 10^{10} h_{72}^{-2} L_\odot$ is the luminosity of a typical bright galaxy, and $\alpha \simeq -1.25$ (Kirshner et al. 1983).

This function is a power law for $L \ll L_\star$, but cuts off rapidly for $L > L_\star$, reflecting the fact that there seems to be a “soft” upper limit to galaxy luminosity. Equation (1.1) implies that the *total* number of galaxies per unit volume diverges; presumably this law must cut off for very small L. However, the total *luminosity* per unit volume, computed by integrating $L\phi(L)dL$ over all L, is finite, and most of this luminosity is due to galaxies with $L > 0.3L_\star$. Because intrinsically bright galaxies can be seen to greater distances than fainter ones, most of the galaxies in a magnitude-limited catalog are quite luminous, with $L \sim L_\star$.

While gravitational dynamics is scale-free, the Schecter function (1.1) does define a characteristic scale: the luminosity $L_\star$. Any theory of galaxy formation must explain the origin of this characteristic luminosity.

1.4 Catalogs & Databases

Some frequently-referenced galaxy catalogs are:

- **NGC**: the 'New General Catalog', now a century old, lists a variety of non-stellar objects, including about 4000 galaxies.

- **UGC**: the 'Uppsala General Catalog' (Nilson 1973), lists positions and parameters for 12939 galaxies.

- **RSA**: the 'Revised Shapley-Ames' catalog (Sandage & Tammann 1987) lists 1246 bright galaxies.

- **RC3**: the 'Third Reference Catalog of Bright Galaxies' (de Vaucouleurs et al. 1991) collects positions, classifications, magnitudes, colors, radial velocities and other information for 23024 galaxies.

- **NBG**: the 'Nearby Bright Galaxies' catalog (Tully 1988) presents the distribution of nearby galaxies in three dimensions.

- **Arp**: the 'Atlas of Peculiar Galaxies' (Arp 1966) presents large-scale images of 338 objects.

On-line data sets are increasingly valuable research tools:

- **NED**: an on-line database of extragalactic objects, found at `http://nedwww.ipac.caltech.edu/index.html`.

- **POSS**: Digitized Palomar Sky Survey images are available at `http://stdatu.stsci.edu/dss`.

- **2MASS**: an infrared all-sky survey, available at `http://www.ipac.caltech.edu/2mass/`.

- **SDSS**: the Sloan Digital Sky Survey, a project to map one-quarter of the entire sky, is avialable at `http://www.sdss.org/`.

Problems

1.1. For the Schecter luminosity function (1.1) with $\alpha = -1.25$ given above, show that half the total luminosity is produced by galaxies brighter than $L \simeq 0.454 L_\star$. Note: this involves an integral you may find difficult to evaluate; if you can't proceed analytically, try evaluating it numerically.

1.2. Again adopting a Schecter function (1.1) with $\alpha = -1.25$, calculate the average galaxy luminosity for a magnitude-limited sample of galaxies.