Contents

Chapter 1

Introduction

Galaxies. They are some of the most beautiful and fascinating objects in the Universe. They come in a large variety of sizes and shapes, colors and brightnesses, from majestic spirals to seemingly boring ellipticals, massive cluster members to dinky little satellites only seen nearby. Every new way that astronomers devise to look at the sky reveals a different view of galaxies, from the familiar optical and near-infrared images dominated by starlight, to the dust emission in the far infrared, and the high-energy processes that shape the far reaches of the wavelength scale. Remarkably, much of the structure of galaxies can be understood using simple physics and the goal of this book is to provide an introduction to the quantitative understanding of galactic structure, formation, and evolution that is derived primarily from chasing down the effects of gravity on stellar systems. Of course, while gravity is arguably the most important fundamental force on the scale of galaxies, it does not suffice to understand the full picture of galaxies and their formation and evolution. The physics of radiation, hydrodynamics, nuclear fusion, chemistry, etc. play a fundamental role as well and we will also discuss their important contributions to shaping galaxies.

1.1 THE WORLD OF GALAXIES

Before we start our sojourn in the realm of galaxies, let's take a quick tour of the types of galaxies found in the Universe. Figure 1.1 displays two very beautiful, famous galaxies: M51 and Cen A. M51 is a *grand-design spiral* galaxy. While the origin of spiral structure in galaxies remains an open problem with likely a variety of solutions, in this case the beautiful spiral structure is most probably caused by the response to the gravity from the companion galaxy at the top of the image. Spiral structure, besides looking pretty, is an important driver of star formation, as the gravitational force of the spiral compresses gas, leading to the formation of new stars within the spirals. These show up as the compact dots along the spiral arms in Figure 1.1, which are small clusters of young stars, traced by their ionized HII emission here.

Cen A is one of the brightest galaxies in the sky and an example of an S0 galaxy, a galaxy somewhere between the extremes of elliptical and spiral galaxies. Its exact classification is still a matter of debate and this illustrates the difficulty we face when studying galaxies. The only data we have is a single snapshot in time from a single perspective, with very limited information on its three-dimensional structure.

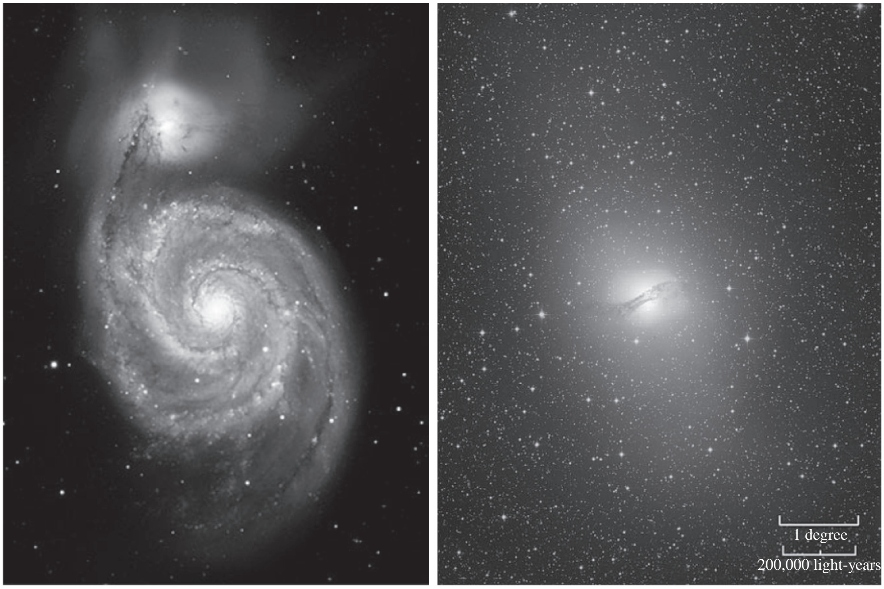

Figure 1.1: M51 (NASA/JPL-Caltech/Univ. of Arizona/DSS/SST) and Cen A (NASA/DOE/Fermi LAT Collaboration, Capella Observatory).

Because no galaxy is a fully relaxed system, *all* galaxies are evolving and many are going through dramatic transformations. Cen A has probably endured a merger in its recent past, leading to a burst of star formation and the fueling of an active galactic nucleus (AGN)—a supermassive black hole with a bright accretion disk—at its center.

While most of the famous galaxies are as large as those pictured in Figure 1.1, many other galaxies are quite a bit smaller. We find many examples of these in our own backyard, as satellite galaxies of the Milky Way. Figure 1.2 shows two examples: the Large Magellanic Cloud (LMC) and the Fornax dwarf galaxy (not to be confused with the Fornax cluster!). The LMC is one of the closest neighbors of the Milky Way and the largest of its satellite galaxies—galaxies caught in the web of the Milky Way's gravitational attraction. The LMC is part of a pair of galaxies that fell into the Milky Way's gravitational field together and its irregular appearance is in large part due to the tidal interactions with its sibling, the Small Magellanic Cloud, and with the Milky Way. The LMC has a prominent bar at its center and was likely a barred spiral galaxy before it started interacting with the Milky Way. The LMC is about 10 times smaller in size and mass than the Milky Way. It has a lot of gas and many areas of active star formation. Some of the most famous star-forming regions are in the LMC.

Fornax is an example of a dwarf spheroidal galaxy, which are the smallest galaxies. Such galaxies are much more diffuse, as can be seen by comparing the Fornax dwarf galaxy to the pictures of M51 or Cen A above, and their masses are dominated by dark matter, making them some of the best places we have to constrain the fundamental

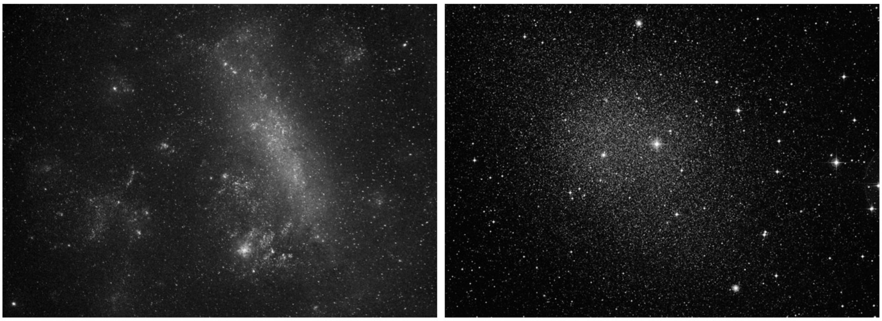

Figure 1.2: The Large Magellanic Cloud (credit: Dylan O'Donnell) and the Fornax dwarf spheroidal (ESO/Digitized Sky Survey 2).

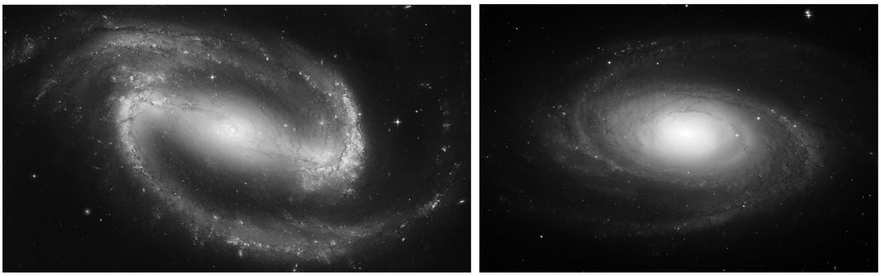

Figure 1.3: NGC 1300 and M81 (both NASA, ESA, and The Hubble Heritage Team STScI/AURA).

nature of dark matter. Fornax in particular is a bit of a dynamical celebrity, because it has a number of globular clusters. If the dark-matter profile in the centers of galaxies has the expected, cuspy shape, then the process of dynamical friction should have caused these clusters to have long since spiraled into the center (Tremaine 1976b). That Fornax still has these globular clusters therefore indicates that the dark-matter density is lower than expected at its center.

Circling back to Milky-Way-sized galaxies, Figure 1.3 gives two more examples of large disk galaxies: NGC 1300 and M81. The most obvious property of NGC 1300 is the rectangular-ish feature at its center, with two prominent spiral arms emanating from its ends. This feature is called a *bar* (for obvious reasons) and it is a common feature of disk galaxies. Overall, about 30% of disk galaxies in the local Universe have strong bars, a fraction that goes down as we look further into the past, showing that bars are a relatively recent (in cosmic time units!) feature of galaxies. Our own Milky Way has a bar at its center, the exact properties of which are still up for debate, but it is far less strong than the bar in NGC 1300. Bars form naturally during the evolution of disk galaxies.

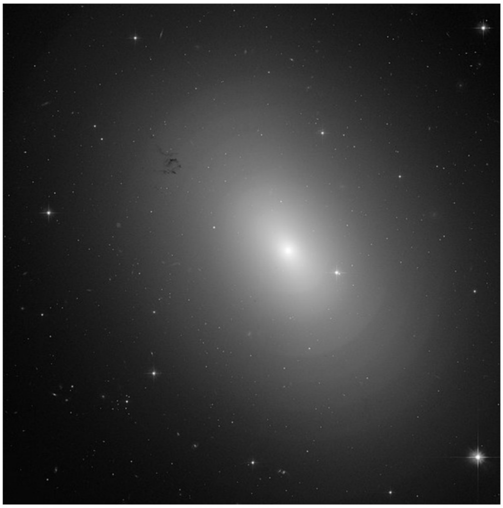

Figure 1.4: NGC 3923 (NASA/ESA Hubble Space telescope).

M81 is a spiral galaxy without an obvious bar at its center. Instead, it has a prominent *bulge*, a spheroidal concentration of mostly old stars, and tightly wound spirals. M81 is part of a group of galaxies much like the Local Group, the set of galaxies that includes the Milky Way and the Andromeda galaxies (which we will typically refer to as M31), their satellites, and some more small galaxies associated with them. M81 interacts with M82 and NGC 3077, a good reminder that almost no galaxy lives in isolation.

We could keep showing pictures of barred and spiral disk galaxies (and of barred-spiral disk galaxies!), but let's look at an example of an elliptical galaxy: NGC 3923 in Figure 1.4. NGC 3923 is a more-interesting-than-usual example of an elliptical galaxy, which normally have smooth, elliptical light distributions without any features. Even though most elliptical galaxies might at first glance therefore seem a little boring, their internal orbital structure can be quite complex. NGC 3923 is especially interesting, because it has multiple shell-like features in its outer parts; such galaxies are known as *shell galaxies*. The presence of shells indicates that the stars are arranged in a structure more akin to layers than in a smooth, continuous distribution like in other elliptical galaxies. Such shell-like features are common in elliptical galaxies, with an estimated 50% of elliptical galaxies displaying faint shells. The shells are an indication that NGC 3923 has experienced a merger with a small satellite and the distribution of orbits of stars in the satellite got re-arranged to give rise to a density profile with sharp edges.

Galaxies are not just made up of single stars, but also contain stellar clusters of various sorts. Because the evolution of these clusters is intimately related to the evolution of their host galaxies, we will also give them some attention in this book. Two

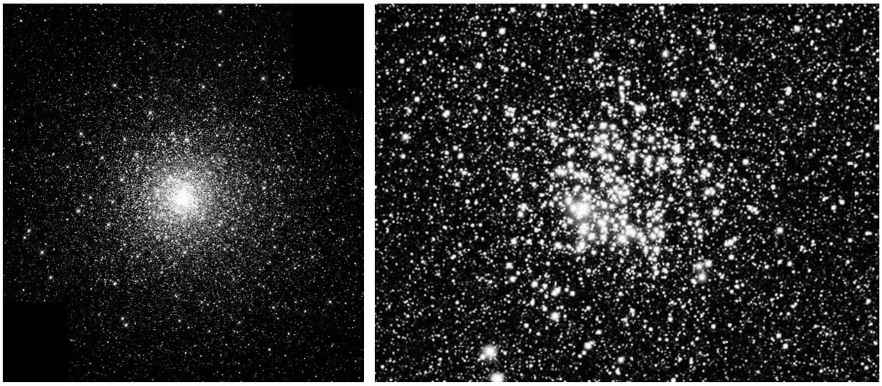

Figure 1.5: M80 (NASA, The Hubble Heritage Team, STScI/AURA) and M11 (NASA).

of the main types of stellar clusters are globular clusters and open clusters. Figure 1.5 gives an example of one of each: the globular cluster M80 and the open cluster M11. It is immediately clear that these are two quite different beasts. Globular clusters are extremely dense, with typical sizes of a few to 10 pc and containing upwards of ten thousand stars (up to a million). The center of M80 is a blob of light, even in this picture taken by the Hubble Space Telescope, because there are too many stars close together to be able to resolve all of them as individual stars in this image. M80 is one of the most massive of the $\approx$ 150 globular clusters in the Milky Way. Globular clusters are old and are found in almost all galaxies, with the number of globular clusters in a galaxy scaling with the total mass (e.g., Harris et al. 2013). Because they are so dense, globular clusters display a rich dynamical phenomenology that is quite different from that of galaxies. Dynamics and stellar evolution are also intimately linked in globular clusters, making them a fine laboratory for stellar evolution and potentially factories for binary black holes such as those seen by LIGO. Globular clusters can also get disrupted by tidal interactions with their host galaxies, leading to the production of narrow stellar streams.

Open clusters are very different from globular clusters. The main difference is that they are much less dense and many of them are only marginally bound. Open clusters dot the disks of star-forming galaxies. They consist of stars born together in a (typically recent) star-formation event, have typical sizes of about 10 pc, and contain a few hundred to tens of thousands of stars. Open clusters are generally only a few hundred million years old, although some survive for many billions of years. The open cluster pictured in Figure 1.5, M11, is about 250 million years old and is a rich open cluster with about 3,000 stars. Open clusters are an important laboratory for simple stellar evolution. Open clusters get easily disrupted by tidal forces and only the most tightly bound therefore survive for billions of years.

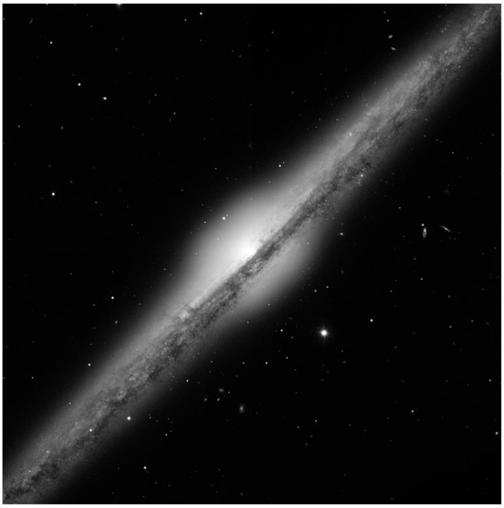

Figure 1.6: NGC 4565, an edge-on disk galaxy (ESO).

1.2 A BRIEF TOUR OF GALAXY OBSERVATIONS

To set the stage for the material covered in this book, we start with a high-level overview of the various components that make up galaxies. The objective here is not to provide a detailed and exhaustive overview of galaxy phenomenology (that will be done in later chapters!), but merely to briefly discuss the size, shape, and contribution to the overall mass budget of different galactic components.

We will focus our overview on large disk galaxies. Large disk galaxies are one of the most important type of galaxies for various reasons: approximately half of all galaxies in the local Universe are disk galaxies, and such galaxies appear to be most efficient at converting gas into stars. Therefore, most stars in the local Universe live in the disks of large disk galaxies. We also live close to the mid-plane of a large disk galaxy, the Milky Way. This provides us with a detailed, close-up view of the structure of such a galaxy. In the Milky Way, we can observe stars from the most luminous giants to the lowest-mass M dwarfs, from the center of the Galaxy to the outskirts of the spherical stellar halo surrounding the disk, and we can study gas in its various atomic and molecular phases. Because galactic disks are "dynamically cold", meaning that the ratio of their velocity dispersion to the typical velocity of a star is small, they are also prone to instabilities that give rise to bars, spiral structure, etc., which are phenomena that we will discuss in later chapters.

Figure 1.6 shows a typical disk galaxy, NGC 4565, seen edge-on. NGC 4565 displays all of the components of a typical disk galaxy. Its structure is dominated by a disk consisting of stars and gas, with a protrusion of stars near the center that is called the bulge. The gas itself cannot be seen in this picture, but its presence can

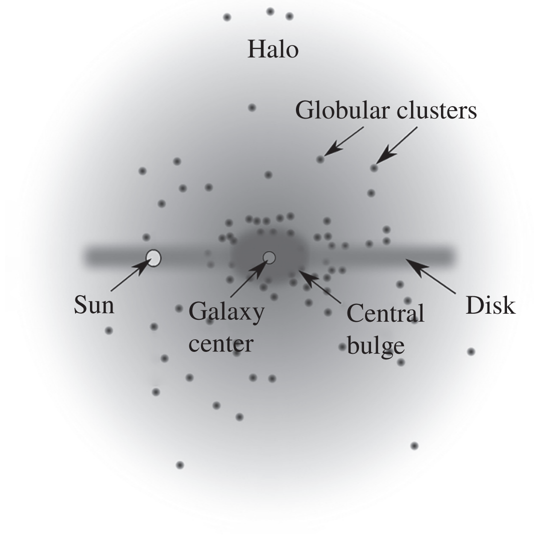

Figure 1.7: A schematic overview of the Milky Way (RJHall at English Wikipedia).

be inferred because gas is traced by dust grains, which redden passing starlight and cause the reddish band close to the disk's mid-plane. NGC 4565 does have a stellar halo (Harmsen et al. 2017), but it is too faint to be seen in this picture. Also not seen in this picture (and never seen *directly*—whatever that means—in any picture of any galaxy) is the spheroidal distribution of dark matter that surrounds the disk and extends to very large distances from the center.

Figure 1.7 provides a schematic overview of a disk galaxy, the Milky Way in particular (but except for the Sun's position, this structure applies to all disk galaxies). This illustration shows the disk edge-on and displays the system of globular cluster that surrounds each galaxy, in addition to the components that we already discussed. The Galactic center is also separately emphasized. We have known for about two decades that the centers of galaxies host supermassive black holes (see Chapter 16), which can be active and surrounded by an accretion disk (such accretion disks are a topic that we will not cover in this book) or inactive and often surrounded by a dense *nuclear star cluster*.

1.2.1 The distribution of stars in galaxies

One of the most basic observations about the disks of galaxies is that they are **exponential**. That is, their light profiles $I(R)$ follow an exponential decline with radius $I(R) = I_0 \exp(-R/h_R)$. This had been known in the mid-1900s, but was most famously discussed by Freeman (1970) "On the disks of spiral and S0 galaxies" (oh,

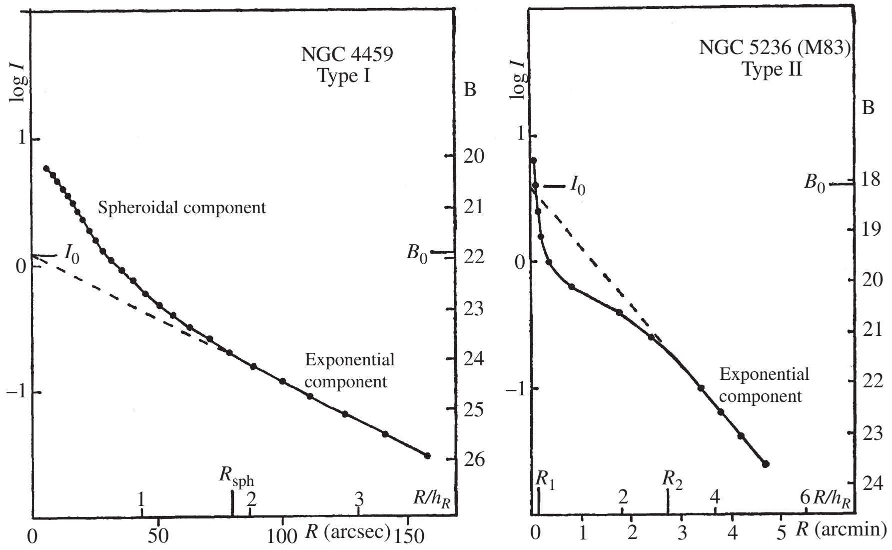

Figure 1.8: Galaxy disks have exponential profiles (Freeman 1970).

to be able to write a paper with a title like that!). Figure 1.8 is the first figure in Freeman's paper, which shows the surface brightness as a function of radius along the major axis in the blue B band. Because surface brightness is given on the y axis as a logarithmic quantity measured in magnitudes, the linear decline implies an exponential decline of the light profile. Both of the shown galaxies only follow the exponential law over a restricted radial range. Near the center they rise precipitously, due to the presence of the bulge (the "spheroidal component" above); the galaxy on the right also has a flattened part of the light profile near the center, which is not uncommon.

The second most important dimension of a disk is its vertical dimension. Vertical for the moment means perpendicular to the two-dimensional plane of the disk, the direction along which the disk is narrowest. Along the vertical direction, the density also falls off quickly in a roughly symmetric manner; the peak of the vertical density occurs at the **mid-plane**, the zero-point of the vertical coordinate. Like for the radial profile, we look at the vertical profile of the surface brightness to get a sense for what the vertical mass distribution is. Figure 1.9 shows a typical result. This figure shows vertical surface-brightness profiles for NGC 4244 at different distances from its center. Again, we see a linear decline at large distances, which implies an exponential fall-off (because the surface brightness in this figure is again a logarithmic quantity). Near the mid-plane the profile flattens and becomes close to constant. The fit that is shown is a sech^2 profile, a hyperbolic secant squared, which is the equilibrium solution of a self-gravitating isothermal disk, as we will see in Chapter 10.4. As we discussed above and will discuss below in more detail, disks contain gas and stars of various ages with different vertical distributions and the simple isothermal—having

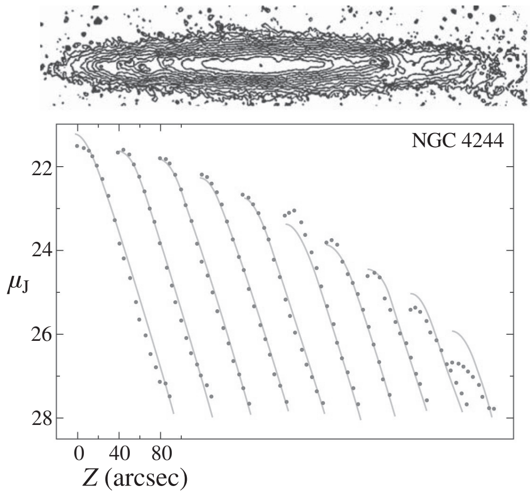

Figure 1.9: NGC 4244: top: a pure-disk galaxy seen edge-on; bottom: vertical surface-brightness profiles at a range of distances from the center; profiles are displaced along the X-axis to avoid overlapping (van der Kruit & Freeman 2011).

the same amount of random motion at each vertical height—can therefore not be entirely correct. The sech^2 profile should therefore not be taken too seriously, but is simply a physically-motivated profile that does a good job of fitting the observations.

The ratio between the scale length h_R of the radial decline and the scale height h_z of the vertical decline is a measure of the thickness of the disk. A typical value is $h_R/h_z \approx 10$, meaning that disks are quite thin.

Whether we use number counts or surface brightness, to translate these observed profiles to mass profiles, we have to assume stellar-population models for how mass is traced by light. This is done by applying a **mass-to-light ratio** M/L that converts the amount of light observed to an amount of (stellar) mass and is usually silently expressed in solar units (the Sun's mass over the Sun's luminosity). The stellar mass-to-light ratio is typically assumed to be constant through the galaxy and is $M/L \approx 3$, but it depends on the passband in which the luminosity is measured. The total mass-to-light ratio in galaxies is much larger and depends on position, because in addition to stars, it includes the dark matter, which adds mass, but does not contribute to the luminosity; the total M/L also includes gas, which in broad optical and near-infrared passbands similarly does not contribute to the luminosity, while adding mass (but generally much less mass than either stars or dark matter; see below). The total mass-to-light ratio depends on position because the fraction of total mass that is dark matter and gas strongly depends on position.

While the radial and vertical profiles of the disk are (close to) exponential, the central bulge is not. Bulges typically have profiles similar to elliptical galaxies, which are modeled as **Sérsic profiles**: $\mu(R) = \mu_0 - b_n R^{1/n}$, where μ is the surface brightness,

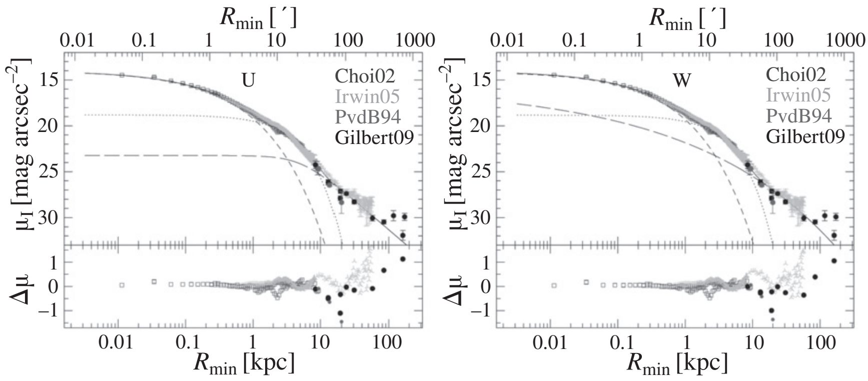

Figure 1.10: Surface-brightness profile of M31 along with a fit with a Sérsic bulge (dashed), exponential disk (dotted) and halo (long dashed) with the combined fit profile as the full curve; halo model is a power-law on the left and Sérsic on the right (Courteau et al. 2011).

μ_0 is the central surface brightness, n is the Sérsic index, and b_n can be computed from the value of n. The case of $n = 4$ is the classic **de Vaucouleurs profile**, which represents the surface brightness profiles of large elliptical galaxies well. Setting $n = 1$, we have an exponential profile.

As an example, Figure 1.10 displays the surface-brightness profile of M31, the closest large disk galaxy outside of the Milky Way. M31's bulge component is a dashed line in fits to this profile with a Sérsic bulge, exponential disk, and a stellar halo (with two different radial profiles in the two panels). The bulge has a Sérsic index of about 2.2 and dominates within 1 kpc, the very central region of the galaxy. The disk, given by the dotted line, starts to dominate the light outside 1 kpc and does so out to 10 kpc. The stellar halo dominates the light outside the disk region.

Given how prominent the stellar halo is outside the disk region, let's take a closer look at this component. Figure 1.11 shows deep observations of some external disk galaxies. These observations are deep enough to reveal the low surface-brightness envelope surrounding these disks (the actual disks are painted in from shallower observations). When fitting the radial surface-brightness profile of these galaxies with an exponential-disk plus a bulge, many of these galaxies have excess light at large radii (> 20 kpc) beyond the exponential disk. This light extends in a spheroidal manner, not a disk, and follows an approximate power-law profile. There is great diversity in the profiles of the stellar halos in galaxies. This is because the stellar halo is believed to form primarily from mergers (accreted material from merging satellite galaxies, or material from the main galaxy disturbed by a merger).

While the stellar halo takes up a large volume, its total stellar mass is much smaller than that of the other main galactic components. The stellar halo typically only accounts for a few percent of the stellar mass of a galaxy and much less than that of the

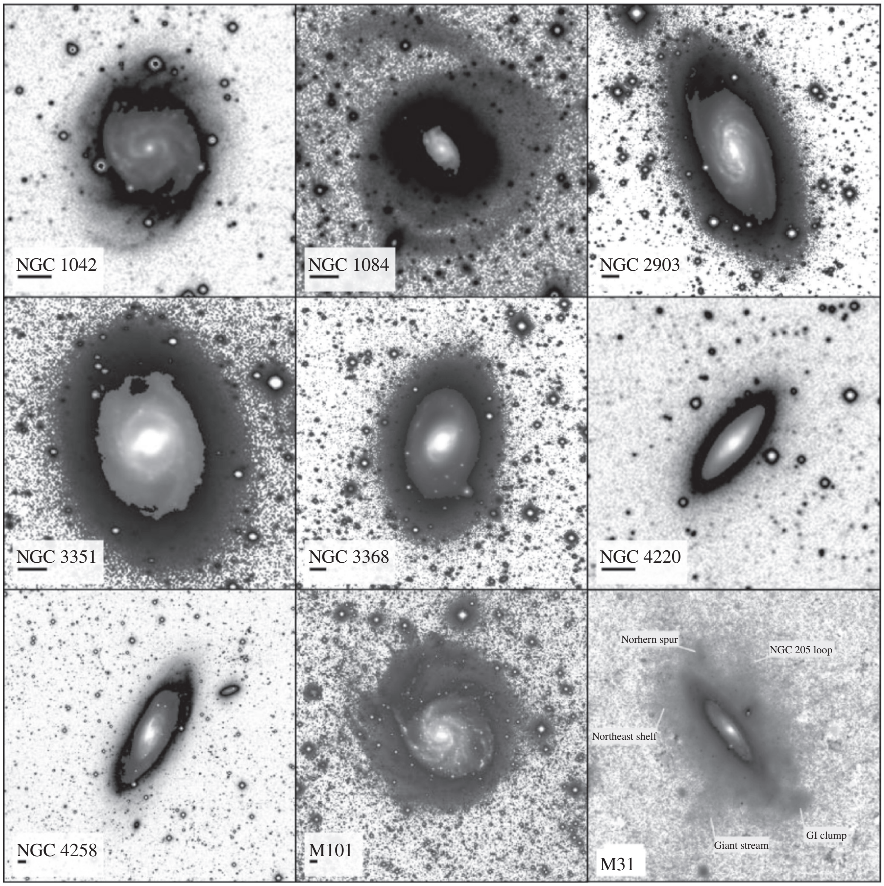

Figure 1.11: Stellar halos (Merritt et al. 2016).

total mass. There is no part of a galaxy where the stellar halo dominates the density, because it is always overwhelmed by either the bulge, disk, dark-matter halo, or the gaseous component.

1.2.2 The distribution of gas in galaxies

All baryonic matter was once in gaseous form, but in large, present-day disk galaxies only about 10% of the baryonic mass is present as cold/warm gas in the interstellar medium. Gas is present in galaxies in different phases and in both atomic and molecular form. Making a precise census of all of the gas in galaxies, in particular the amount of hot halo gas, is difficult.

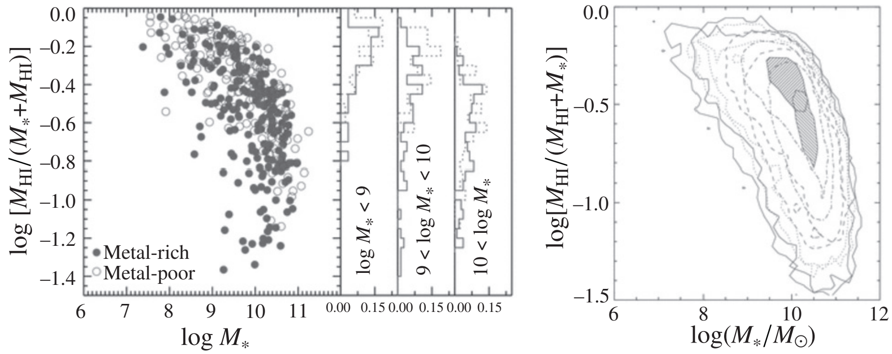

Figure 1.12: The gas content of galaxies (Zhang et al. 2009). Left panel: HI gas mass fraction vs. stellar mass for metal-rich (red) and metal-poor (blue) galaxies, for galaxies with direct HI observations. Right panel: HI mass fraction vs. stellar mass for star-forming galaxies with indirect HI measurements.

Stars form from cold molecular gas. Cold gas is contained in a disk component much like the stellar disk component that we discussed above. Most of the gas is atomic hydrogen, or HI. Figure 1.12 shows the cold-gas content (HI in particular) as a function of stellar mass for a sample of galaxies in the local Universe. The Milky Way's stellar mass is about $6 \times 10^{10}\, M_\odot$ or $\log(M_*/M_\odot) \approx 10.8$ (Bovy & Rix 2013); gas makes up about 10% of the baryonic disk mass in the Milky Way. Figure 1.12 shows that the gas fraction rises as one goes to lower mass galaxies and the dynamics of gas and its interaction with stars is thus much more important in lower mass galaxies than it is in the Milky Way.

In the Milky Way, we can make a reasonably complete census of the interstellar medium near the Sun. The main components are: atomic hydrogen (HI), ionized hydrogen (HII), and molecular hydrogen (H_2), contributing $\approx 1.01\,\mathrm{cm}^{-3}$, $\approx 0.015\,\mathrm{cm}^{-3}$, and $\approx 0.15\,\mathrm{cm}^{-3}$, respectively in the mid-plane (McKee et al. 2015). The atomic hydrogen comes in cold and warm phases that constitute $\approx$ 80% and $\approx$ 20% of the local HI density. Converting these number densities in the mid-plane to a mass density, we find that the mid-plane gas density is about $0.041\, M_\odot\,\mathrm{pc}^{-3}$, approximately the same as that in stars ($\approx 0.040\, M_\odot\,\mathrm{pc}^{-3}$; Bovy 2017b). The molecular gas layer has an exponential scale height that is approximately $h_z = 100\,\mathrm{pc}$, the cold component of HI has about the same thickness, the warm HI has $h_z \approx 300\,\mathrm{pc}$, while the ionized gas is contained in a much thicker layer. The total local gas surface density is $\approx 14\, M_\odot\,\mathrm{pc}^{-2}$ with HI contributing $\approx 11\, M_\odot\,\mathrm{pc}^{-2}$, HII $\approx 2\, M_\odot\,\mathrm{pc}^{-2}$, and H_2 adding $\approx 1\, M_\odot\,\mathrm{pc}^{-2}$.

The radial distribution of these gas components is much less certain. The radial surface density of HI is shown in the left panel of Figure 1.13. Thus, the density of HI is almost constant within 10 kpc or at most displays a shallow decline; outside

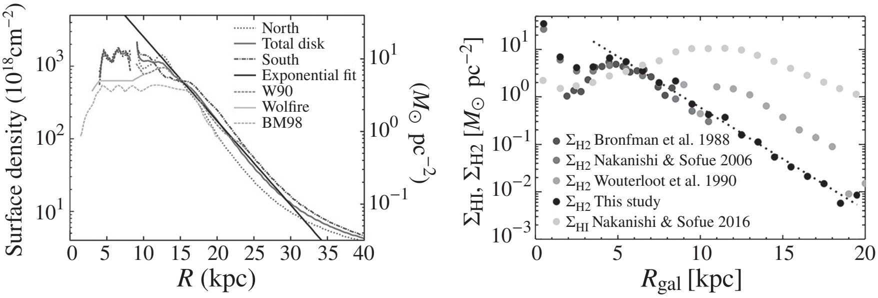

Figure 1.13: The surface density of neutral hydrogen (Kalberla & Kerp 2009; left panel) and of molecular hydrogen (Miville-Deschênes et al. 2017; right panel) in the Milky Way.

of 10 kpc it falls off exponentially. But note that there are significant asymmetries between different parts of the distribution.

A smaller fraction of the ISM is contained in molecular gas (about 10% near the Sun). The radial profile of the molecular gas is similar to that of the HI: it is approximately constant in the inner Galaxy and drops off exponentially at larger radii, as shown in the right panel of Figure 1.13. But the molecular gas has a shorter scale length than the HI, so very little of it is found outside of 15 kpc. Almost all of the molecular gas is contained in molecular clouds.

1.2.3 The distribution of mass in galaxies

Now that we have a good sense of the stellar and gas distribution in a typical disk galaxy, let's take a look at the largest contributor to the galactic mass distribution: the dark-matter halo. Dark matter is a largely unknown constituent of the Universe, likely a new particle, that overall is about 5 times more abundant (e.g., Planck Collaboration et al. 2016) than ordinary matter (sometimes called "baryonic matter" although this misses the ordinary, fermionic matter that is, however, negligible in mass compared to its baryonic counterpart). In galaxies such as the Milky Way, there is more than ten times more dark matter than ordinary matter, with the remaining baryonic matter likely in warm and hot phases in the interstellar and intergalactic medium (e.g., Shull et al. 2012). We know about the presence of dark matter solely through its gravitational influence and this book will cover how we have learned and are continuing to investigate the distribution of dark matter in galaxies.

To get a sense of the distribution of dark matter, we will plot the density and enclosed mass of different components of the Milky Way. We use the mass model for the Milky Way from McMillan (2017). This model has a bulge, disk, and dark-matter halo potential (ignoring the contributions from the stellar halo and including those from the gas together with the stellar disk). In the top panel of Figure 1.14, we look at the density of the different components in the mid-plane of the Milky Way

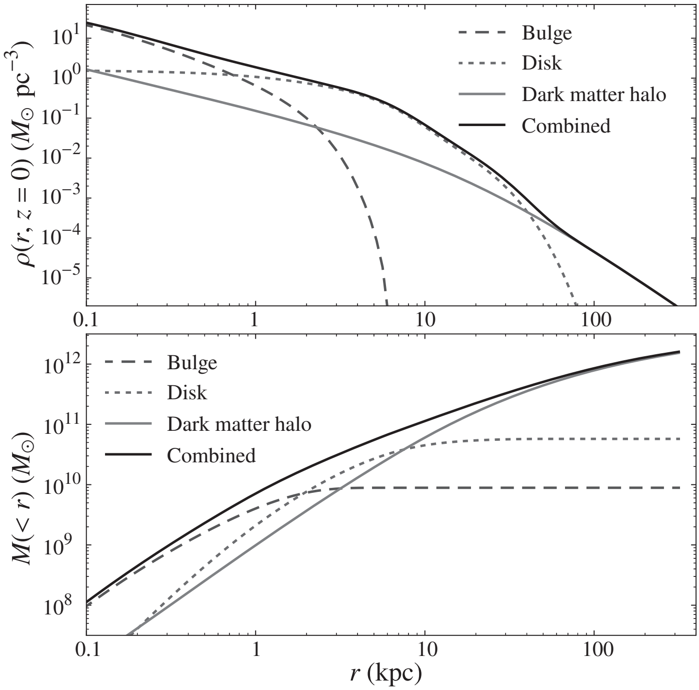

Figure 1.14: The mass profile of the Milky Way.

(at $z = 0$) as well as the total density. Much like in M31 above, the bulge component dominates the density within 1 kpc, but becomes less important after that. The stellar disk dominates the density between 1 kpc and about 30 kpc, after which the dark-matter halo dominates.

The total density near the Sun (at ≈ 8 kpc from the center) is about 0.1 $M_\odot$ pc^{-3}, with only about 1/10th of that contributed by dark matter. The bottom panel of Figure 1.14 shows the total mass enclosed within a given radius for the different components and for the total mass. The total mass in the bulge+disk is approximately equal to the total mass in the dark-matter halo within 10 kpc from the center. Outside of this, the dark-matter halo dominates the mass and at the edge of the Milky Way, around 250 kpc from the center, there is more than ten times as much dark matter as there is ordinary matter. We will have much more to say about the distribution of dark matter in later chapters.

(continued...)

Index