

# 1. Introduction and Overview

## 1.1 Introduction

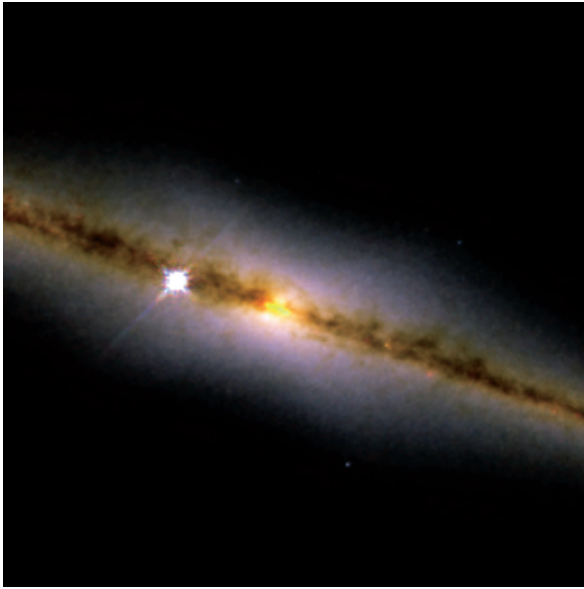
The Milky Way, the galaxy in which we live, is but one of many galaxies. As a matter of fact, the Milky Way, also called the Galaxy, is a fairly average representative of the class of spiral galaxies. Two other examples of spiral galaxies are shown in Fig. 1.1 and Fig. 1.2, one of which we are viewing from above (face-on), the other from the side (edge-on). These are all stellar systems in which the majority of stars are confined to a relatively thin disk. In our own Galaxy, this disk can be seen as the band of stars stretched across the night sky, which led to it being named the Milky Way. Besides such disk galaxies, there is a second major class of luminous stellar systems, the elliptical galaxies. Their properties differ in many respects from those of the spirals.

It was less than a hundred years ago that astronomers first realized that objects exist outside our Milky Way and that our world is significantly larger than the size of the Milky Way. In fact, galaxies are mere islands in the Universe: the diameter of our Galaxy<sup>1</sup> (and other galaxies) is much smaller than the average separation between luminous galaxies. The discovery of the existence of other stellar systems and their variety of morphologies raised the question of the origin and evolution of these galaxies. Is there anything between the galaxies, or is it just empty space? Are there any other cosmic bodies besides galaxies? Questions like these motivated us to explore the Universe as a whole and its evolution. Is our

<sup>1</sup>We shall use the terms “Milky Way” and “Galaxy” synonymously throughout.



**Fig. 1.1.** The spiral galaxy NGC 1232 may resemble our Milky Way if it were to be observed from “above” (face-on). This image, observed with the VLT, has a size of  $6'.8 \times 6'.8$ , corresponding to a linear size of 60 kpc at its distance of 30 Mpc. If this was our Galaxy, our Sun would be located at a distance of 8.0 kpc from the center, orbiting around it at a speed of  $\sim 220$  km/s. A full revolution would take us about  $230 \times 10^6$  years. The bright knots seen along the spiral arms of this galaxy are clusters of newly-formed stars, similar to bright young star clusters in our Milky Way. The different, more reddish, color of the inner part of this galaxy indicates that the average age of the stars there is higher than in the outer parts. The small galaxy at the lower left edge of the image is a companion galaxy that is distorted by the gravitational tidal forces caused by the spiral galaxy



**Fig. 1.2.** We see the spiral galaxy NGC 4013 from the side (edge-on); an observer looking at the Milky Way from a direction which lies in the plane of the stellar disk (“from the side”) may have a view like this. The disk is clearly visible, with its central region obscured by a layer of dust. One also sees the central bulge of the galaxy. As will be discussed at length later on, spiral galaxies like this one are surrounded by a halo of matter which is observed only through its gravitational action, e.g., by affecting the velocity of stars and gas rotating around the center of the galaxy

Universe finite or infinite? Does it change over time? Does it have a beginning and an end? Mankind has long been fascinated by these questions about the origin and the history of our world. But for only a few decades have we been able to approach these questions in an empirical manner. As we shall discuss in this book, many of the questions have now been answered. However, each answer raises yet more questions, as we aim towards an ever increasing understanding of the physics of the Universe.

The stars in our Galaxy have very different ages. The oldest stars are about 12 billion years old, whereas in some regions stars are still being born today: for instance in the well-known Orion nebula. Obviously, the stellar content of our Galaxy has changed over time. To understand the formation and evolution of the Galaxy a view of its (and thus our own) past would be useful.

Unfortunately, this is physically impossible. However, due to the finite speed of light, we see objects at large distances in an earlier state, as they were in the past. One can now try to identify and analyze such distant galaxies, which may have been the progenitors of galaxies like our own Galaxy, in this way reconstructing the main aspects of the history of the Milky Way. We will never know the exact initial conditions that led to the evolution of the Milky Way, but we may be able to find some characteristic conditions. Emerging from such initial states, cosmic evolution should produce galaxies similar to our own, which we would then be able to observe from the outside. On the other hand, only within our own Galaxy can we study the physics of galaxy evolution *in situ*.

We are currently witnessing an epoch of tremendous discoveries in astronomy. The technical capabilities in observation and data reduction are currently evolving at an enormous pace. Two examples taken from ground-based optical astronomy should serve to illustrate this.

In 1993 the first 10-m class telescope, the Keck telescope, was commissioned, the first increase in light-collecting power of optical telescopes since the completion of the 5-m mirror on Mt. Palomar in 1948. Now, just a decade later, about ten telescopes of the 10-m class are in use, and even more are soon to come. In recent years, our capabilities to find very distant, and thus very dim, objects and to examine them in detail have improved immensely thanks to the capability of these large optical telescopes.

A second example is the technical evolution and size of optical detectors. Since the introduction of CCDs in astronomical observations at the end of the 1970s, which replaced photographic plates as optical detectors, the sensitivity, accuracy, and data rate of optical observations have increased enormously. At the end of the 1980s, a camera with  $1000 \times 1000$  pixels (*picture elements*) was considered a wide-field instrument. In 2003 a camera called Megacam began operating; it has  $(18\,000)^2$  pixels and images a square degree of the sky at a sampling rate of  $0''.2$  in a single exposure. Such a camera produces roughly 100 GB of data every night, the reduction of which requires fast computers and vast storage capacities. But it is not only optical astronomy that is in a phase of major development; there has also been huge progress in instrumentation in other wavebands. Space-based observing platforms are playing

a crucial role in this. We will consider this topic in Sect. 1.3.

These technical advances have led to a vast increase in knowledge and insight in astronomy, especially in extragalactic astronomy and cosmology. Large telescopes and sensitive instruments have opened up a window to the distant Universe. Since any observation of distant objects is inevitably also a view into the past, due to the finite speed of light, studying objects in the early Universe has become possible. Today, we can study galaxies which emitted the light we observe at a time when the Universe was less than 10% of its current age; these galaxies are therefore in a very early evolutionary stage. We are thus able to observe the evolution of galaxies throughout the past history of the Universe. We have the opportunity to study the history of galaxies and thus that of our own Milky Way. We can examine at which epoch most of the stars that we observe today in the local Universe have formed because the history of star formation can be traced back to early epochs. In fact, it has been found that star formation is largely hidden from our eyes and only observable with space-based telescopes operating in the far-infrared waveband.

One of the most fascinating discoveries of recent years is that most galaxies harbor a black hole in their center, with a characteristic mass of millions or even billions of solar masses – so-called supermassive black holes. Although as soon as the first quasars were found in 1963 it was proposed that only processes around a supermassive black hole would be able to produce the huge amount of energy emitted by these ultra-luminous objects, the idea that such black holes exist in normal galaxies is fairly recent. Even more surprising was the finding that the black hole mass is closely related to the other properties of its parent galaxy, thus providing a clear indication that the evolution of supermassive black holes is closely linked to that of their host galaxies.

Detailed studies of individual galaxies and of associations of galaxies, which are called galaxy groups or clusters of galaxies, led to the surprising result that these objects contain considerably more mass than is visible in the form of stars and gas. Analyses of the dynamics of galaxies and clusters show that only 10–20% of their mass consists of stars, gas and dust that we are able to observe in emission or absorption. The largest fraction of their mass, however, is invisible. Hence, this hidden mass is called *dark matter*. We know of its presence

only through its gravitational effects. The dominance of dark matter in galaxies and galaxy clusters was established in recent years from observations with radio, optical and X-ray telescopes, and it was also confirmed and quantified by other methods. However, we do not know what this dark matter consists of; the unambiguous evidence for its existence is called the “dark matter problem”.

The nature of dark matter is one of the central questions not only in astrophysics but also poses a challenge to fundamental physics, unless the “dark matter problem” has an astronomical solution. Does dark matter consist of non-luminous celestial bodies, for instance burned-out stars? Or is it a new kind of matter? Have astronomers indirectly proven the existence of a new elementary particle which has thus far escaped detection in terrestrial laboratories? If dark matter indeed consists of a new kind of elementary particle, which is the common presumption today, it should exist in the Milky Way as well, in our immediate vicinity. Therefore, experiments which try to directly detect the constituents of dark matter with highly sensitive and sophisticated detectors have been set up in underground laboratories. Physicists and astronomers are eagerly awaiting the commissioning of the Large Hadron Collider (LHC), a particle accelerator at the European CERN research center which, from 2007 on, will produce particles at significantly higher energies than accessible today. The hope is to find an elementary particle that could serve as a candidate constituent of dark matter.

Without doubt, the most important development in recent years is the establishment of a standard model of cosmology, i.e., the science of the Universe as a whole. The Universe is known to expand and it has a finite age; we now believe that we know its age with a precision of as little as a few percent – it is  $t_0 = 13.7$  Gyr. The Universe has evolved from a very dense and very hot state, the Big Bang, expanding and cooling over time. Even today, echoes of the Big Bang can be observed, for example in the form of the cosmic microwave background radiation. Accurate observations of this background radiation, emitted some 380 000 years after the Big Bang, have made an important contribution to what we know today about the composition of the Universe. However, these results raise more questions than they answer: only  $\sim 4\%$  of the energy content of the Universe can be accounted for by matter which is well-known from

other fields of physics, the *baryonic matter* that consists mainly of atomic nuclei and electrons. About 25% of the Universe consists of dark matter, as we already discussed in the context of galaxies and galaxy clusters. Recent observational results have shown that the mean density of dark matter dominates over that of baryonic matter also on cosmic scales.

Even more surprising than the existence of dark matter is the discovery that about 70% of the Universe consists of something that today is called vacuum energy, or dark energy, and that is closely related to the cosmological constant introduced by Albert Einstein. The fact that various names do exist for it by no means implies that we have any idea what this dark energy is. It reveals its existence exclusively in its effect on cosmic expansion, and it even dominates the expansion dynamics at the current epoch. Any efforts to estimate the density of dark energy from fundamental physics have failed hopelessly. An estimate of the vacuum energy density using quantum mechanics results in a value that is roughly *120 orders of magnitude* larger than the value derived from cosmology. For the foreseeable future observational cosmology will be the only empirical probe for dark energy, and an understanding of its physical nature will probably take a substantial amount of time. The existence of dark energy may well pose the greatest challenge to fundamental physics today.

In this book we will present a discussion of the extragalactic objects found in astronomy, starting with the Milky Way which, being a typical spiral galaxy, is considered a prototype of this class of stellar systems. The other central topic in this book is a presentation of modern astrophysical cosmology, which has experienced tremendous advances in recent years. Methods and results will be discussed in parallel. Besides providing an impression of the fascination that arises from astronomical observations and cosmological insights, astronomical methods and physical considerations will be our prime focus. We will start in the next section with a concise overview of the fields of extragalactic astronomy and cosmology. This is, on the one hand, intended to whet the reader's appetite and curiosity, and on the other hand to introduce some facts and technical terms that will be needed in what follows but which are discussed in detail only later in the book. In Sect. 1.3 we will describe some of the most important telescopes used in extragalactic astronomy today.

## 1.2 Overview

### 1.2.1 Our Milky Way as a Galaxy

The Milky Way is the only galaxy which we are able to examine in detail. We can resolve individual stars and analyze them spectroscopically. We can perform detailed studies of the interstellar medium (ISM), such as the properties of molecular clouds and star-forming regions. We can quantitatively examine extinction and reddening by dust. Furthermore, we can observe the local dynamics of stars and gas clouds as well as the properties of satellite galaxies (such the Magellanic Clouds). Finally, the Galactic center at a distance of only 8 kpc<sup>2</sup> gives us the unique opportunity to examine the central region of a galaxy at very high resolution. Only through a detailed understanding of our own Galaxy can we hope to understand the properties of other galaxies. Of course, we implicitly assume that the physical processes taking place in other galaxies obey the same laws of physics that apply to us. If this were not the case, we would barely have a chance to understand the physics of other objects in the Universe, let alone the Universe as a whole. We will return to this point shortly.

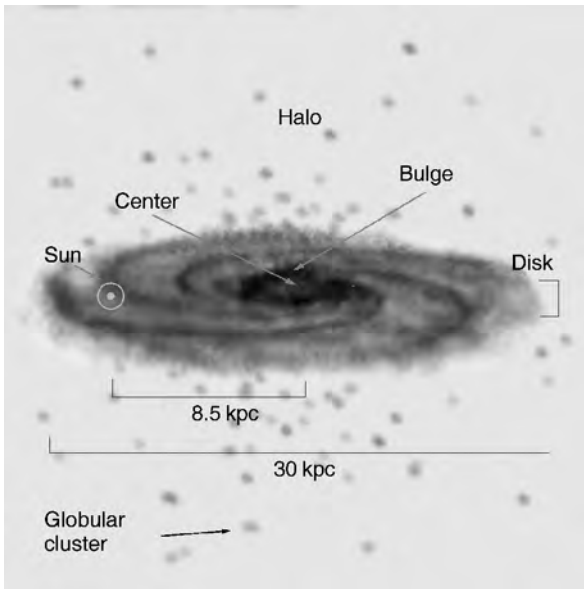
We will first discuss the properties of our own Galaxy. One of the main problems here, and in astronomy in general, is the determination of the distance to an object. Thus we will start by considering this topic. From the analysis of the distribution of stars and gas in the Milky Way we will then derive its structure. It is found that the Galaxy consists of several distinct components:

- a thin disk of stars and gas with a radius of about 20 kpc and a scale-height of about 300 pc, which also hosts the Sun;
- a  $\sim 1$  kpc thick disk, which contains a different stellar population compared to the thin disk;
- a central bulge, as is also found in other spiral galaxies;
- and a nearly spherical halo which contains most of the globular clusters and some old stars.

Figure 1.3 shows a schematic view of our Milky Way and its various components. For a better visual impression, Figs. 1.1 and 1.2 show two spiral galaxies, the

<sup>2</sup>One parsec (1 pc) is the common unit of distance in astronomy, with  $1 \text{ pc} = 3.086 \times 10^{18} \text{ cm}$ . Also used are  $1 \text{ kpc} = 10^3 \text{ pc}$ ,  $1 \text{ Mpc} = 10^6 \text{ pc}$ ,  $1 \text{ Gpc} = 10^9 \text{ pc}$ . Other commonly used units and constants are listed in Appendix C.

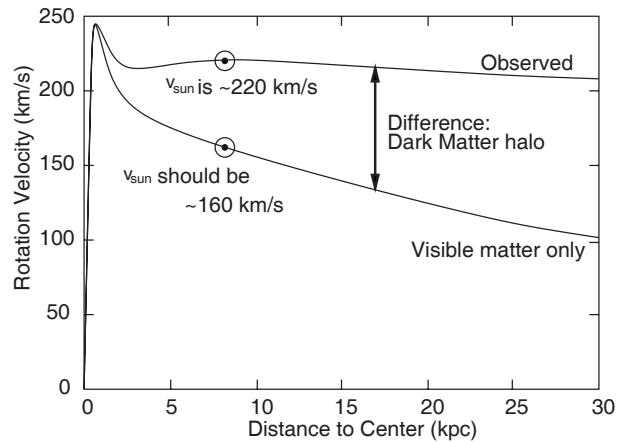




**Fig. 1.3.** Schematic structure of the Milky Way consisting of the disk, the central bulge with the Galactic center, and the spherical halo in which most of the globular clusters are located. The Sun orbits around the Galactic center at a distance of about 8 kpc

former viewed from “above” (face-on) and the latter from the “side” (edge-on). In the former case, the spiral structure, from which this kind of galaxy derives its name, is clearly visible. The bright knots in the spiral arms are regions where young, luminous stars have recently formed. The image shows an obvious color gradient: the galaxy is redder in the center and bluest in the spiral arms – while star formation is currently taking place in the spiral arms, we find mainly old stars towards the center, especially in the bulge.

The Galactic disk rotates, with rotational velocity  $V(R)$  depending on the distance  $R$  from the center. We can estimate the mass of the Galaxy from the distribution of the stellar light and the mean mass-to-light ratio of the stellar population, since gas and dust represent less than  $\sim 10\%$  of the mass of the stars. From this mass estimate we can predict the rotational velocity as a function of radius simply from Newtonian mechanics. However, the observed rotational velocity of the Sun around the Galactic center is significantly higher than would be expected from the observed mass distribution. If  $M(R_0)$  is the mass inside a sphere around the Galactic center with radius  $R_0 \approx 8$  kpc, then the rotational



**Fig. 1.4.** The upper curve is the observed rotation curve  $V(R)$  of our Galaxy, i.e., the rotational velocity of stars and gas around the Galactic center as a function of their galacto-centric distance. The lower curve is the rotation curve that we would predict based solely on the observed stellar mass of the Galaxy. The difference between these two curves is ascribed to the presence of dark matter, in which the Milky Way disk is embedded

velocity from Newtonian mechanics<sup>3</sup> is

$$V_0 = \sqrt{\frac{G M(R_0)}{R_0}}. \quad (1.1)$$

From the visible matter in stars we would expect a rotational velocity of  $\sim 160$  km/s, but we observe  $V_0 \sim 220$  km/s (see Fig. 1.4). This, and the shape of the rotation curve  $V(R)$  for larger distances  $R$  from the Galactic center, indicates that our Galaxy contains significantly more mass than is visible in the form of stars.<sup>4</sup> This additional mass is called *dark matter*. Its physical nature is still unknown. The main candidates are weakly interacting elementary particles like those postulated by some elementary particle theories, but they have yet not been detected in the laboratory. Macroscopic objects (i.e., celestial bodies) are also in principle possible candidates if they emit very little light. We will discuss experiments which allow us to identify such macroscopic

<sup>3</sup>We use standard notation:  $G$  is the Newtonian gravitational constant,  $c$  the speed of light.

<sup>4</sup>Strictly speaking, (1.1) is valid only for a spherically symmetric mass distribution. However, the rotational velocity for an oblate density distribution does not differ much, so we can use this relation as an approximation.

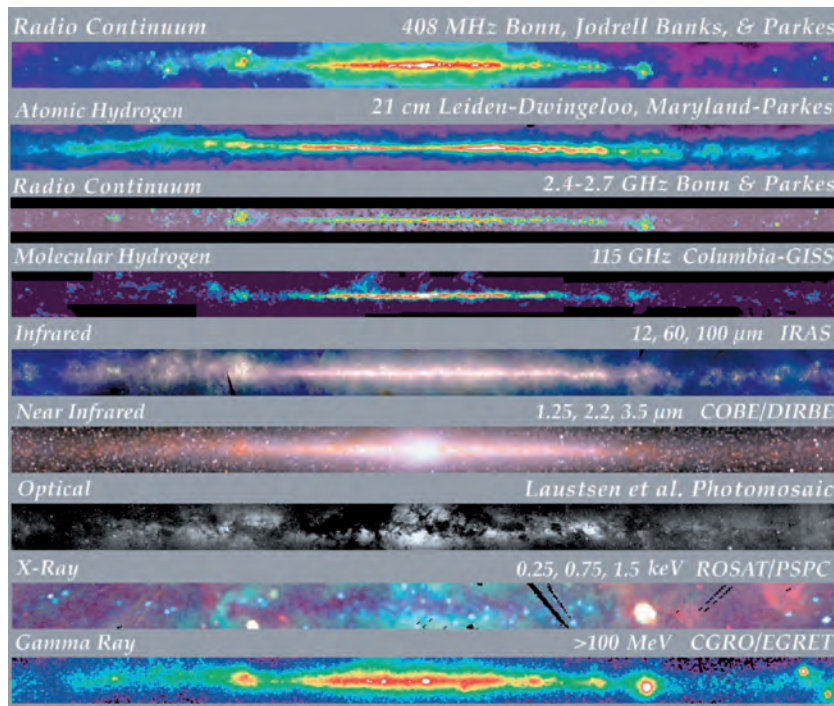
objects and come to the conclusion that the solution of the dark matter problem probably can not be found in astronomy, but rather most likely in particle physics.

The stars in the various components of our Galaxy have different properties regarding their age and their chemical composition. By interpreting this fact one can infer some aspects of the evolution of the Galaxy. The relatively young age of the stars in the thin disk, compared to that of the older population in the bulge, suggests different phases in the formation and evolution of the Milky Way. Indeed, our Galaxy is a highly dynamic object that is still changing today. We see cold gas falling into the Galactic disk and hot gas outflowing. Currently the small neighboring Sagittarius dwarf galaxy is being torn apart in the tidal gravitational field of the Milky Way and will merge with it in the (cosmologically speaking) near future.

One cannot see far through the disk of the Galaxy at optical wavelengths due to extinction by dust. Therefore, the immediate vicinity of the Galactic center can be examined only in other wavebands, especially the infrared (IR) and the radio parts of the electromag-

netic spectrum (see also Fig. 1.5). The Galactic center is a highly complex region but we have been able to study it in recent years thanks to various substantial improvements in IR observations regarding sensitivity and angular resolution. Proper motions, i.e., changes of the positions on the sky with time, of bright stars close to the center have been observed. They enable us to determine the mass  $M$  in a volume of radius  $\sim 0.1$  pc to be  $M(0.1 \text{ pc}) \sim 3 \times 10^6 M_{\odot}$ . Although the data do not allow us to make a totally unambiguous interpretation of this mass concentration there is no plausible alternative to the conclusion that the center of the Milky Way harbors a supermassive black hole (SMBH) of roughly this mass. And yet this SMBH is far less massive than the ones that have been found in many other galaxies.

Unfortunately, we are unable to look at our Galaxy from the outside. This view from the inside renders it difficult to observe the global properties of the Milky Way. The structure and geometry of the Galaxy, e.g., its spiral arms, are hard to identify from our location. In addition, the extinction by dust hides large parts of the Galaxy from our view (see Fig. 1.6), so that the global



**Fig. 1.5.** The Galactic disk observed in nine different wavebands. Its appearance differs strongly in the various images; for example, the distribution of atomic hydrogen and of molecular gas is much more concentrated towards the Galactic plane than the distribution of stars observed in the near-infrared, the latter clearly showing the presence of a central bulge. The absorption by dust at optical wavelengths is also clearly visible and can be compared to that in Fig. 1.2



**Fig. 1.6.** The galaxy Dwingeloo 1 is only five times more distant than our closest large neighboring galaxy, Andromeda, yet it was not discovered until the 1990s because it hides behind the Galactic center. The absorption in this direction and numerous bright stars prevented it being discovered earlier. The figure shows an image observed with the Isaac Newton Telescope in the V-, R-, and I-bands

parameters of the Milky Way (like its total luminosity) are difficult to measure. These parameters are estimated much better from outside, i.e., in other similar spiral galaxies. In order to understand the large-scale properties of our Galaxy, a comparison with similar galaxies which we can examine in their entirety is extremely helpful. Only by combining the study of the Milky Way with that of other galaxies can we hope to fully understand the physical nature of galaxies and their evolution.

### 1.2.2 The World of Galaxies

Next we will discuss the properties of other galaxies. The two main types of galaxies are spirals (like the Milky Way, see also Fig. 1.7) and elliptical galaxies (Fig. 1.8). Besides these, there are additional classes such as irregular and dwarf galaxies, active galaxies, and starburst galaxies, where the latter have a very high star-formation rate in comparison to normal galaxies. These classes differ not only in their morphology, which forms the basis for their classification, but also in their physical properties such as color (indicating a different stellar content), internal reddening (depending on their dust



**Fig. 1.7.** NGC 2997 is a typical spiral galaxy, with its disk inclined by about  $45^\circ$  with respect to the line-of-sight. Like most spiral galaxies it has two spiral arms; they are significantly bluer than other parts of the galaxy. This is caused by ongoing star formation in these regions so that young, hot and thus blue stars are present in the arms, whereas the center of the galaxy, especially the bulge, consists mainly of old stars





**Fig. 1.8.** M87 is a very luminous elliptical galaxy in the center of the Virgo Cluster, at a distance of about 18 Mpc. The diameter of the visible part of this galaxy is about 40 kpc; it is significantly more massive than the Milky Way ( $M > 3 \times 10^{12} M_{\odot}$ ). We will frequently refer to this galaxy: it is not only an excellent example of a central cluster galaxy but also a representative of the family of “active galaxies”. It is a strong radio emitter (radio astronomers also know it as Virgo A), and it has an optical jet in its center

content), amount of interstellar gas, star-formation rate, etc. Galaxies of different morphologies have evolved in different ways.

Spiral galaxies are stellar systems in which active star formation is still taking place today, whereas elliptical galaxies consist mainly of old stars – their star formation was terminated a long time ago. The S0 galaxies, an intermediate type, show a disk similar to that of spiral galaxies but like ellipticals they consist mainly of old stars, i.e., stars of low mass and low temperature. Ellipticals and S0 galaxies together are often called *early-type galaxies*, whereas spirals are termed *late-type galaxies*. These names do not imply any interpretation but exist only for historical reasons.

The disks of spiral galaxies rotate differentially. As for the Milky Way, one can determine the mass from the rotational velocity using the Kepler law (1.1). One finds that, contrary to the expectation from the distribution of light, the rotation curve does not decline at larger distances from the center. *Like our own Galaxy, spiral galaxies contain a large amount of dark matter; the visible matter is embedded in a halo of dark matter.* We can only get rough estimates of the extent of this halo, but there are strong indications that it is substantially larger than the extent of the visual matter. For instance, the rotation curve is flat up to the largest radii where one still finds gas to measure the velocity. Studying dark matter in elliptical galaxies is more complicated, but the existence of dark halos has also been proven for ellipticals.

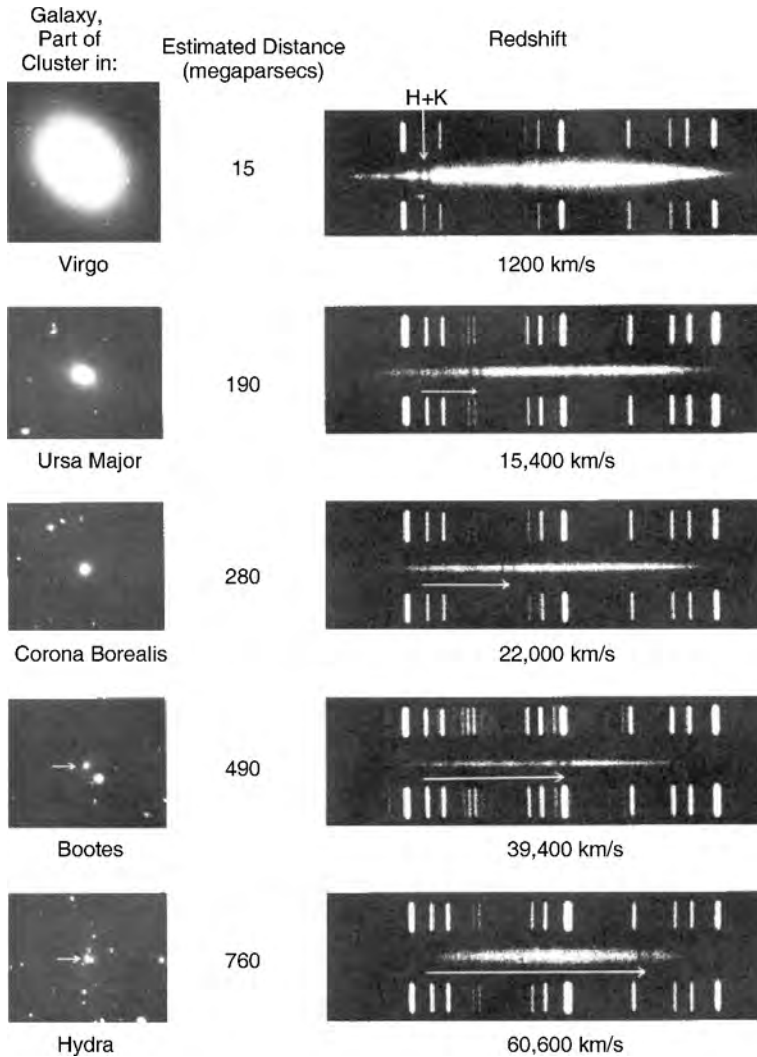
The Hertzsprung–Russell diagram of stars, or their color–magnitude diagram (see Appendix B), has turned out to be the most important diagram in stellar astrophysics. The fact that most stars are aligned along a one-dimensional sequence, the main sequence, led to the conclusion that, for main-sequence stars, the luminosity and the surface temperature are not independent parameters. Instead, the properties of such stars are in principle characterized by only a single parameter: the stellar mass. We will also see that the various properties of galaxies are not independent parameters. Rather, dynamical properties (such as the rotational velocity of spirals) are closely related to the luminosity. These scaling relations are of similar importance to the study of galaxies as the Hertzsprung–Russell diagram is for stars. In addition, they turn out to be very convenient tools for the determination of galaxy distances.

Like our Milky Way, other galaxies also seem to harbor a SMBH in their center. We obtained the astonishing result that the mass of such a SMBH is closely related to the velocity distribution of stars in elliptical galaxies or in the bulge of spirals. The physical reason for this close correlation is as yet unknown, but it strongly suggests a joint evolution of galaxies and their SMBHs.

### 1.2.3 The Hubble Expansion of the Universe

The radial velocity of galaxies, measured by means of the Doppler shift of spectral lines (Fig. 1.9), is positive for nearly all galaxies, i.e., they appear to be moving away from us. In 1928, Edwin Hubble discovered that





**Fig. 1.9.** The spectra of galaxies show characteristic spectral lines, e.g., the H + K lines of calcium. These lines, however, do not appear at the wavelengths measured in the laboratory but are in general shifted towards longer wavelengths. This is shown here for a set of sample galaxies, with distance increasing from top to bottom. The shift in the lines, interpreted as being due to the Doppler effect, allows us to determine the relative radial velocity – the larger it is, the more distant the galaxy is. The discrete lines above and below the spectra are for calibration purposes only

this escape velocity  $v$  increases with the distance of the galaxy. He identified a linear relation between the radial velocity  $v$  and the distance  $D$  of galaxies, called a Hubble law,

$$v = H_0 D, \quad (1.2)$$

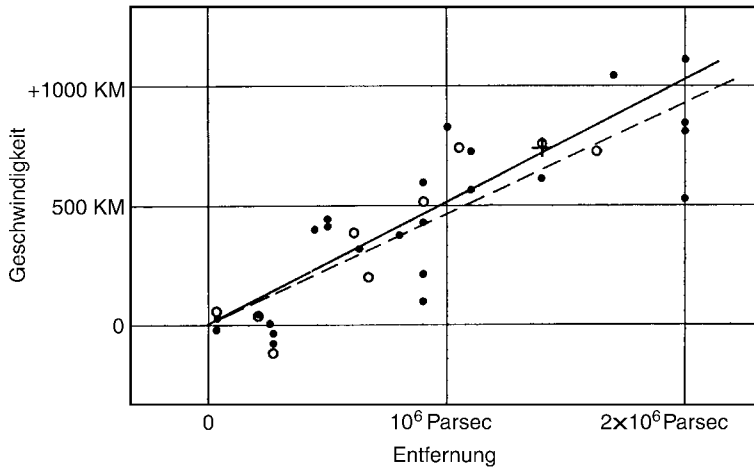
where  $H_0$  is a constant. If we plot the radial velocity of galaxies against their distance, as is done in the Hubble diagram of Fig. 1.10, the resulting points are approximated by a straight line, with the slope being determined by the constant of proportionality,  $H_0$ , which is called the *Hubble constant*. The fact that all galaxies seem

to move away from us with a velocity which increases linearly with their distance is interpreted such that the Universe is expanding. We will see later that this *Hubble expansion* of the Universe is a natural property of cosmological world models.

The value of  $H_0$  has been determined with appreciable precision only in recent years, yielding the conservative estimate

$$60 \text{ km s}^{-1} \text{ Mpc}^{-1} \lesssim H_0 \lesssim 80 \text{ km s}^{-1} \text{ Mpc}^{-1}, \quad (1.3)$$

obtained from several different methods which will be discussed later. The error margins vary for the differ-



**Fig. 1.10.** The original 1929 version of the Hubble diagram shows the radial velocity of galaxies as a function of their distance. The reader may notice that the velocity axis is labeled with erroneous units – of course they should read km/s. While the radial (escape) velocity is easily measured by means of the Doppler shift in spectral lines, an accurate determination of distances is much more difficult; we will discuss methods of distance determination for galaxies in Sect. 3.6. Hubble has underestimated the distances considerably, resulting in too high a value for the Hubble constant. Only very few and very close galaxies show a blueshift, i.e., they move towards us; one of these is Andromeda (= M31)

ent methods and also for different authors. The main problem in determining  $H_0$  is in measuring the absolute distance of galaxies, whereas Doppler shifts are easily measurable. If one assumes (1.2) to be valid, the radial velocity of a galaxy is a measure of its distance. One defines the *redshift*,  $z$ , of an object from the wavelength shift in spectral lines,

$$z := \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0}, \quad \lambda_{\text{obs}} = (1+z)\lambda_0, \quad (1.4)$$

with  $\lambda_0$  denoting the wavelength of a spectral transition in the rest-frame of the emitter and  $\lambda_{\text{obs}}$  the observed wavelength. For instance, the Lyman- $\alpha$  transition, i.e., the transition from the first excited level to the ground state in the hydrogen atom is at  $\lambda_0 = 1216 \text{ \AA}$ . For small redshifts,

$$v \approx zc, \quad (1.5)$$

whereas this relation has to be modified for large redshifts, together with the interpretation of the redshift itself.<sup>5</sup> Combining (1.2) and (1.5), we obtain

$$D \approx \frac{zc}{H_0} \approx 3000 z h^{-1} \text{ Mpc}, \quad (1.6)$$

<sup>5</sup>What is observed is the wavelength shift of spectral lines. Depending on the context, it is interpreted either as a radial velocity of a source moving away from us – for instance, if we measure the radial velocity of stars in the Milky Way – or as a cosmological escape velocity, as is the case for the Hubble law. It is in principle impossible to distinguish between these two interpretations, because a galaxy not only takes part in the cosmic expansion but it

where the uncertainty in determining  $H_0$  is parametrized by the scaled Hubble constant  $h$ , defined as

$$H_0 = h \, 100 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (1.7)$$

Distance determinations based on redshift therefore always contain a factor of  $h^{-1}$ , as seen in (1.6). It needs to be emphasized once more that (1.5) and (1.6) are valid only for  $z \ll 1$ ; the generalization for larger redshifts will be discussed in Sect. 4.3. Nevertheless,  $z$  is also a measure of distance for large redshifts.

## 1.2.4 Active Galaxies and Starburst Galaxies

A special class of galaxies are the so-called active galaxies which have a very strong energy source in their center (active galactic nucleus, AGN). The best-known representatives of these AGNs are the quasars, objects typically at high redshift and with quite exotic properties. Their spectrum shows strong emission lines which can be extremely broad, with a relative width of  $\Delta\lambda/\lambda \sim 0.03$ . The line width is caused by very high

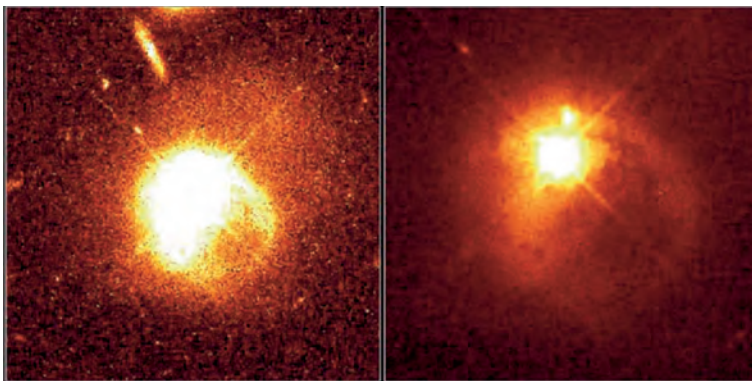
can, in addition, have a so-called peculiar velocity. We will therefore use the words “Doppler shift” and “redshift”, respectively, and “radial velocity” depending on the context, but always keeping in mind that both are measured by the shift of spectral lines. Only when observing the distant Universe where the Doppler shift is fully dominated by the cosmic expansion will we exclusively call it “redshift”.

random velocities of the gas which emits these line: if we interpret the line width as due to Doppler broadening resulting from the superposition of lines of emitting gas with a very broad velocity distribution, we obtain velocities of typically  $\Delta v \sim 10\,000$  km/s. The central source of these objects is much brighter than the other parts of the galaxy, making these sources appear nearly point-like on optical images. Only with the Hubble Space Telescope (HST) did astronomers succeed in detecting structure in the optical emission for a large sample of quasars (Fig. 1.11).

Many properties of quasars resemble those of Seyfert type I galaxies, which are galaxies with a very luminous nucleus and very broad emission lines. For this reason, quasars are often interpreted as extreme members of this class. The total luminosity of quasars is extremely large, with some of them emitting more than a thousand times the luminosity of our Galaxy. In addition, this radiation must originate from a very small spatial region whose size can be estimated, e.g., from the variability time-scale of the source. Due to these and other properties which will be discussed in Chap. 5, it is concluded that the nuclei of active galaxies must contain a supermassive black hole as the central powerhouse. The radiation is produced by matter falling towards this black hole, a process called accretion, thereby converting its gravitational potential energy into kinetic energy.

If this kinetic energy is then transformed into internal energy (i.e., heat) as happens in the so-called accretion disk due to friction, it can get radiated away. This is in fact an extremely efficient process of energy production. For a given mass, the accretion onto a black hole is about 10 times more efficient than the nuclear fusion of hydrogen into helium. AGNs often emit radiation across a very large portion of the electromagnetic spectrum, from radio up to X-ray and gamma radiation.

Spiral galaxies still form stars today; indeed star formation is a common phenomenon in galaxies. In addition, there are galaxies with a considerably higher star-formation rate than “normal” spirals. These galaxies are undergoing a burst of star formation and are thus known as *starburst galaxies*. Their star-formation rates are typically between 10 and  $300 M_{\odot}/\text{yr}$ , whereas our Milky Way gives birth to about  $2 M_{\odot}/\text{yr}$  of new stars. This vigorous star formation often takes place in localized regions, e.g., in the vicinity of the center of the respective galaxy. Starbursts are substantially affected, if not triggered, by disturbances in the gravitational field of the galaxy, such as those caused by galaxy interactions. Such starburst galaxies (see Fig. 1.12) are extremely luminous in the far-infrared (FIR); they emit up to 98% of their total luminosity in this part of the spectrum. This happens by dust emission: dust in these galaxies absorbs a large proportion of the energetic UV radiation



**Fig. 1.11.** The quasar PKS 2349 is located at the center of a galaxy, its host galaxy. The diffraction spikes (diffraction patterns caused by the suspension of the telescope’s secondary mirror) in the middle of the object show that the center of the galaxy contains a point source, the actual quasar, which is significantly brighter than its host galaxy. The galaxy shows

clear signs of distortion, visible as large and thin tidal tails. The tails are caused by a neighboring galaxy that is visible in the right-hand image, just above the quasar; it is about the size of the Large Magellanic Cloud. Quasar host galaxies are often distorted or in the process of merging with other galaxies. The two images shown here differ in their brightness contrast





**Fig. 1.12.** Arp 220 is the most luminous object in the local Universe. Originally cataloged as a peculiar galaxy, the infrared satellite IRAS later discovered its enormous luminosity in the infrared (IR). Arp 220 is the prototype of ultra-luminous infrared galaxies (ULIRGs). This near-IR image taken with the Hubble Space Telescope (HST) unveils the structure of this object. With two colliding spiral galaxies in the center of Arp 220, the disturbances in the interstellar medium caused by this collision trigger a starburst. Dust in the galaxy absorbs most of the ultraviolet (UV) radiation from the young hot stars and re-emits it in the IR

produced in the star-formation region and then re-emits this energy in the form of thermal radiation in the FIR.

### 1.2.5 Voids, Clusters of Galaxies, and Dark Matter

The likelihood of galaxies interacting (Fig. 1.13) is enhanced by the fact that galaxies are not randomly distributed in space. The projection of galaxies on the celestial sphere, for instance, shows a distinct structure. In addition, measuring the distances of galaxies allows a determination of their three-dimensional distribution. One finds a strong correlation of the galaxy positions. There are regions in space that have a very high galaxy density, but also regions where nearly no galaxies are seen at all. The latter are called *voids*. Such voids can have diameters of up to  $30 h^{-1}$  Mpc.

*Clusters of galaxies* are gravitationally bound systems of a hundred or more galaxies in a volume of diameter  $\sim 2 h^{-1}$  Mpc. Clusters predominantly contain early-type galaxies, so there is not much star formation taking place any more. Some clusters of galaxies seem to be circular in projection, others have a highly elliptical or irregular distribution of galaxies; some even have more than one center. The cluster of galaxies closest to us is the Virgo Cluster, at a distance of  $\sim 18$  Mpc; it is a cluster with an irregular galaxy distribution. The closest regular cluster is Coma, at a distance of  $\sim 90$  Mpc.<sup>6</sup> Coma (Fig. 1.14) contains about 1000 luminous galaxies, of which 85% are early-type galaxies.

<sup>6</sup>The distances of these two clusters are not determined from redshift measurements, but by direct methods that will be discussed in Sect. 3.6; such direct measurements are one of the most successful methods of determining the Hubble constant.



**Fig. 1.13.** Two spiral galaxies interacting with each other. NGC 2207 (on the left) and IC 2163 are not only close neighbors in projection: the strong gravitational tidal interaction they are exerting on each other is clearly visible in the pronounced tidal arms, particularly visible to the right of the right-hand galaxy. Furthermore, a bridge of stars is seen to connect these two galaxies, also due to tidal gravitational forces. This image was taken with the Hubble Space Telescope



**Fig. 1.14.** The Coma cluster of galaxies, at a distance of roughly 90 Mpc from us, is the closest massive regular cluster of galaxies. Almost all objects visible in this image are galaxies associated with the cluster – Coma contains more than a thousand luminous galaxies

In 1933, Fritz Zwicky measured the radial velocities of the galaxies in Coma and found that they have a dispersion of about 1000 km/s. From the total luminosity of all its galaxies the mass of the cluster can be estimated. If the stars in the cluster galaxies have an average mass-to-light ratio ( $M/L$ ) similar to that of our Sun, we would conclude  $M = (M_{\odot}/L_{\odot})L$ . However, stars in early-type galaxies are on average slightly less massive than the Sun and thus have a slightly higher  $M/L$ .<sup>7</sup> Thus, the above mass estimate needs to be increased by a factor of  $\sim 10$ .

Zwicky then estimated the mass of the cluster by multiplying the luminosity of its member galaxies with the mass-to-light ratio. From this mass and the size of the cluster, he could then estimate the velocity that a galaxy needs to have in order to escape from the gravitational field of the cluster – the escape velocity. He found that the characteristic peculiar velocity of cluster galaxies (i.e., the velocity relative to the mean velocity) is substantially larger than this escape velocity. In this case, the galaxies of the cluster would fly apart on a time-scale of about  $10^9$  years – the time it takes a galaxy to

cross through the cluster once – and, consequently, the cluster would dissolve. However, since Coma seems to be a relaxed cluster, i.e., it is in equilibrium and thus its age is definitely larger than the dynamical time-scale of  $10^9$  years, Zwicky concluded that the Coma cluster contains significantly more mass than the sum of the masses of its galaxies. Using the virial theorem<sup>8</sup> he was able to estimate the mass of the cluster from the velocity distribution of the galaxies. This was the first clear indicator of the existence of dark matter.

X-ray satellites later revealed that clusters of galaxies are strong sources of X-ray radiation. They contain hot gas, with temperatures ranging from  $10^7$  K up to  $10^8$  K (Fig. 1.15). This gas temperature is another measure for the depth of the cluster's potential well, since the hotter the gas is, the deeper the potential well has to be to prevent the gas from escaping via evaporation. Mass estimates based on the X-ray temperature result in values that are comparable to those from the velocity dispersion of the cluster galaxies, clearly confirming the hypothesis of the existence of dark matter in clusters. A third method for determining cluster masses, the so-called gravitational lensing effect, utilizes the fact that light is deflected in a gravitational field. The angle through which light rays are bent due to the presence of a massive object depends on the mass of that object. From observation and analysis of the gravitational lensing effect in clusters of galaxies, cluster masses are derived that are in agreement with those from the two other methods. Therefore, clusters of galaxies are a second class of cosmic objects whose mass is dominated by dark matter.

Clusters of galaxies are cosmologically young structures. Their dynamical time-scale, i.e., the time in which the mass distribution in a cluster settles into an equilibrium state, is estimated as the time it takes a member galaxy to fully cross the cluster once. With a characteristic velocity of  $v \sim 1000$  km/s and a diameter of  $2R \sim 2$  Mpc one thus finds

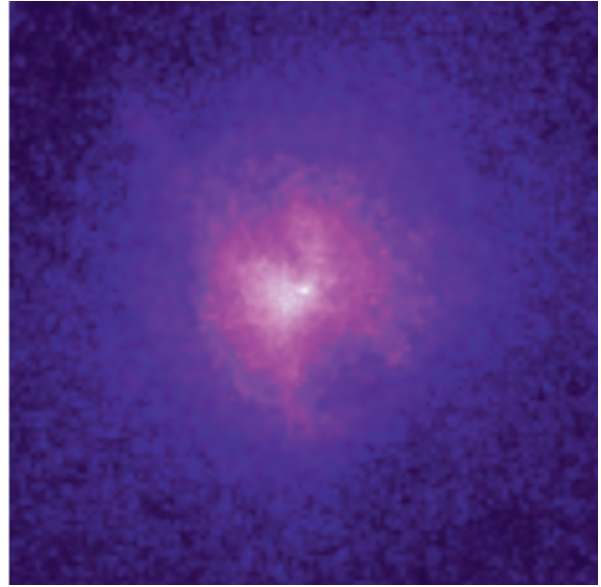
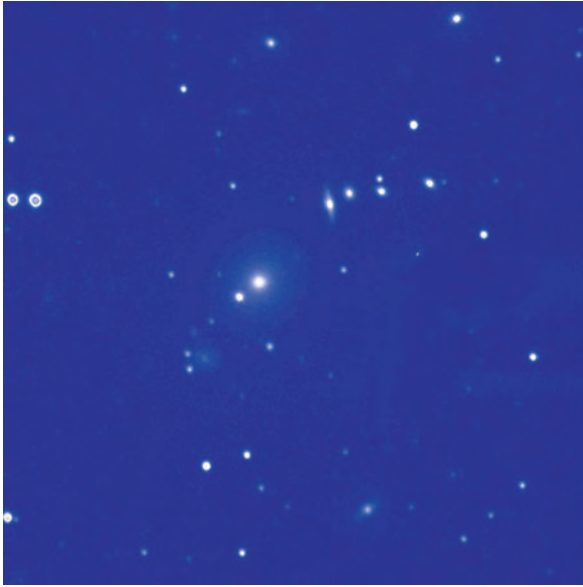
$$t_{\text{dyn}} \sim \frac{2R}{v} \sim 2 \times 10^9 \text{ yr} . \quad (1.9)$$

<sup>8</sup>The virial theorem in its simplest form says that, for an isolated dynamical system in a stationary state of equilibrium, the kinetic energy is just half the potential energy,

$$E_{\text{kin}} = \frac{1}{2} |E_{\text{pot}}| . \quad (1.8)$$

In particular, the system's total energy is  $E_{\text{tot}} = E_{\text{kin}} + E_{\text{pot}} = E_{\text{pot}}/2 = -E_{\text{kin}}$ .

<sup>7</sup>In Chap. 3 we will see that for stars in spiral galaxies  $M/L \sim 3M_{\odot}/L_{\odot}$  on average, while for those in elliptical galaxies a larger value of  $M/L \sim 10M_{\odot}/L_{\odot}$  applies. Here and throughout this book, mass-to-light ratios are quoted in Solar units.



**Fig. 1.15.** The Hydra A cluster of galaxies. The left-hand figure shows an optical image, the one on the right an image taken with the X-ray satellite Chandra. The cluster has a redshift of  $z \approx 0.054$  and is thus located at a distance of about

250 Mpc. The X-ray emission originates from gas at a temperature of  $40 \times 10^6$  K which fills the space between the cluster galaxies. In the center of the cluster, the gas is cooler by about 15%

As we will later see, the Universe is about  $14 \times 10^9$  years old. During this time galaxies have not had a chance to cross the cluster many times. Therefore, clusters still contain, at least in principle, information about their initial state. Most clusters have not had the time to fully relax and evolve into a state of equilibrium that would be largely independent of their initial conditions. Comparing this with the time taken for the Sun to rotate around the center of the Milky Way – about  $2 \times 10^8$  years – galaxies thus have had plenty of time to reach their state of equilibrium.

Besides massive clusters of galaxies there are also galaxy groups, which sometimes contain only a few luminous galaxies. Our Milky Way is part of such a group, the Local Group, which also contains M31 (Andromeda) which is another dominant galaxy, as well as some far less luminous galaxies such as the Magellanic Clouds. Some groups of galaxies are very compact, i.e., their galaxies are confined within a very small volume (Fig. 1.16). Interactions between these galaxies cause the lifetimes of many such groups to be much smaller than the age of the Universe, and the galaxies in such groups will merge.

### 1.2.6 World Models and the Thermal History of the Universe

Quasars, clusters of galaxies, and nowadays even single galaxies are also found at very high redshifts where the simple Hubble law (1.2) is no longer valid. It is therefore necessary to generalize the distance–redshift relation. This requires considering world models as a whole, which are also called cosmological models. The dominant force in the Universe is gravitation. On the one hand, weak and strong interactions both have an extremely small (subatomic) range, and on the other hand, electromagnetic interactions do not play a role on large scales since the matter in the Universe is on average electrically neutral. Indeed, if it was not, currents would immediately flow to balance net charge densities. The accepted theory of gravitation is the theory of General Relativity (GR), formulated by Albert Einstein in 1915.

Based on the two postulates that (1) our place in the Universe is not distinguished from other locations and that (2) the distribution of matter around us is isotropic, at least on large scales, one can construct





**Fig. 1.16.** The galaxy group HCG87 belongs to the class of so-called compact groups. In this HST image we can see three massive galaxies belonging to this group: an edge-on spiral in the lower part of the image, an elliptical galaxy to the lower right, and another spiral in the upper part. The small spiral in the center is a background object and therefore does not belong to the group. The two lower galaxies have an active galactic nucleus, whereas the upper spiral seems to be undergoing a phase of star formation. The galaxies in this group are so close together that in projection they appear to touch. Between the galaxies, gas streams can be detected. The galaxies are disturbing each other, which could be the cause of the nuclear activity and star formation. The galaxies are bound in a common gravitational potential and will heavily interfere and presumably merge on a cosmologically small time-scale, which means in only a few orbits, with an orbit taking about  $10^8$  years. Such merging processes are of utmost importance for the evolution of the galaxy population

homogeneous and isotropic world models (so-called Friedmann–Lemaître models) that obey the laws of General Relativity. Expanding world models that contain the Hubble expansion result from this theory naturally. Essentially, these models are characterized by three parameters:

- the current expansion rate of the Universe, i.e., the Hubble constant  $H_0$ ;

- the current mean matter density of the Universe  $\rho_m$ , often parametrized by the dimensionless *density parameter*

$$\Omega_m = \frac{8\pi G}{3H_0^2} \rho_m; \quad (1.10)$$

- and the density of the so-called vacuum energy, described by the cosmological constant  $\Lambda$  or by the corresponding density parameter of the vacuum

$$\Omega_\Lambda = \frac{\Lambda}{3H_0^2}. \quad (1.11)$$

The cosmological constant was originally introduced by Einstein to allow stationary world models within GR. After the discovery of the Hubble expansion he called the introduction of  $\Lambda$  into his equations his greatest blunder. In quantum mechanics  $\Lambda$  attains a different interpretation, that of an energy density of the vacuum.

The values of the cosmological parameters are known quite accurately today (see Chap. 8), with values of  $\Omega_m \approx 0.3$  and  $\Omega_\Lambda \approx 0.7$ . The discovery of a non-vanishing  $\Omega_\Lambda$  came completely unexpectedly. To date, all attempts have failed to compute a reasonable value for  $\Omega_\Lambda$  from quantum mechanics. By that we mean a value which has the same order-of-magnitude as the one we derive from cosmological observations. In fact, simple and plausible estimates lead to a value of  $\Lambda$  that is  $\sim 10^{120}$  times larger than that obtained from observation, a tremendously bad estimate indeed. This huge discrepancy is probably one of the biggest challenges in fundamental physics today.

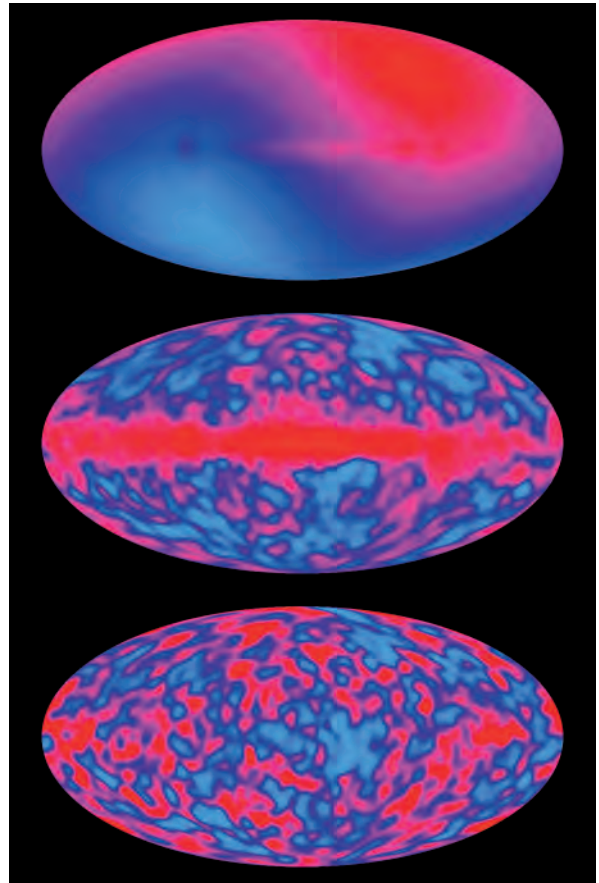
According to the Friedmann–Lemaître models, the Universe used to be smaller and hotter in the past, and it has continuously cooled down in the course of expansion. We are able to trace back the cosmic expansion under the assumption that the known laws of physics were also valid in the past. From that we get the Big Bang model of the Universe, according to which our Universe has evolved out of a very dense and very hot state, the so-called *Big Bang*. This world model makes a number of predictions that have been verified convincingly:

1. About 1/4 of the baryonic matter in the Universe should consist of helium which formed about 3 min after the Big Bang, while most of the rest consists

of hydrogen. This is indeed the case: the mass fraction of helium in metal-poor objects, whose chemical composition has not been significantly modified by processes of stellar evolution, is about 24%.

2. From the exact fraction of helium one can derive the number of neutrino families – the more neutrino species that exist, the larger the fraction of helium will be. From this, it was derived in 1981 that there are 3 kinds of neutrinos. This result was later confirmed by particle accelerator experiments.
3. Thermal radiation from the hot early phase of the Universe should still be measurable today. Predicted in 1946 by George Gamow, it was discovered by Arno Penzias and Robert Wilson in 1965. The corresponding photons have propagated freely after the Universe cooled down to about 3000 K and the plasma constituents combined to neutral atoms, an epoch called recombination. As a result of cosmic expansion, this radiation has cooled down to about  $T_0 \approx 2.73$  K. This microwave radiation is nearly perfectly isotropic, once we subtract the radiation which is emitted locally by the Milky Way (see Fig. 1.17). Indeed, measurements from the COBE satellite showed that the cosmic microwave background (CMB) is the most accurate blackbody spectrum ever measured.
4. Today's structures in the Universe have evolved out of very small density fluctuations in the early cosmos. The seeds of structure formation must have already been present in the early phases of cosmic evolution. These density fluctuations should also be visible as small temperature fluctuations in the microwave background emitted about 380 000 years after the Big Bang at the epoch of recombination. In fact, COBE was the first to observe these predicted anisotropies (see Fig. 1.17). Later experiments, especially the WMAP satellite, observed the structure of the microwave background at much improved angular resolution and verified the theory of structure formation in the Universe in detail (see Sect. 8.6).

With these predictions so impressively confirmed, in this book we will exclusively consider this cosmological model; currently there is no competing model of the Universe that could explain these very basic cosmological observations in such a natural way. In addition, this model does not seem to contradict any fundamental observation in cosmology. However, as the existence of



**Fig. 1.17.** Temperature distribution of the cosmic microwave background on the sky as measured by the COBE satellite. The uppermost image shows a dipole distribution; it originates from the Earth's motion relative to the rest-frame of the CMB. We move at a speed of  $\sim 600$  km/s relative to that system, which leads to a dipole anisotropy with an amplitude of  $\Delta T/T \sim v/c \sim 2 \times 10^{-3}$  due to the Doppler effect. If this dipole contribution is subtracted, we get the map in the middle which clearly shows the emission from the Galactic disk. Since this emission has a different spectral energy distribution (it is not a blackbody of  $T \sim 3$  K), it can also be subtracted to get the temperature map at the bottom. These are the primordial fluctuations of the CMB, with an amplitude of about  $\Delta T/T \sim 2 \times 10^{-5}$

a non-vanishing vacuum energy density shows, together with a matter density  $\rho_m$  that is about six times the mean baryon density in the Universe (which can be derived from the abundance of the chemical elements formed in the Big Bang), the physical nature of about 95% of the content of our Universe is not yet understood.

The CMB photons we receive today had their last physical interaction with matter when the Universe was about  $3.8 \times 10^5$  years old. Also, the most distant galaxies and quasars known today (at  $z \sim 6.5$ ) are strikingly young – we see them at a time when the Universe was less than a tenth of its current age. The exact relation between the age of the Universe at the time of the light emission and the redshift depends on the cosmological parameters  $H_0$ ,  $\Omega_m$ , and  $\Omega_\Lambda$ . In the special case that  $\Omega_m = 1$  and  $\Omega_\Lambda = 0$ , called the *Einstein–de Sitter model*, one obtains

$$t(z) = \frac{2}{3H_0} \frac{1}{(1+z)^{3/2}}. \quad (1.12)$$

In particular, the age of the Universe today (i.e., at  $z = 0$ ) is, according to this model,

$$t_0 = \frac{2}{3H_0} \approx 6.5 \times 10^9 h^{-1} \text{ yr}. \quad (1.13)$$

The Einstein–de Sitter (EdS) model is the simplest world model and we will sometimes use it as a reference, but recent observations suggest that  $\Omega_m < 1$  and  $\Omega_\Lambda > 0$ . The mean density of the Universe in the EdS model is

$$\rho_0 = \rho_{\text{cr}} \equiv \frac{3H_0^2}{8\pi G} \approx 1.9 \times 10^{-29} h^2 \text{ g cm}^{-3}, \quad (1.14)$$

hence it is really, really small.

### 1.2.7 Structure Formation and Galaxy Evolution

The low amplitude of the CMB anisotropies implies that the inhomogeneities must have been very small at the epoch of recombination, whereas today's Universe features very large density fluctuations, at least on scales of clusters of galaxies. Hence, the density field of the cosmic matter must have evolved. This structure evolution occurs because of gravitational instability, in that an overdense region will expand more slowly than the mean Universe due to its self-gravity. Therefore, any relative overdensity becomes amplified in time. The growth of density fluctuations in time will then cause the formation of large-scale structures, and the gravitational instability is also responsible for the formation of galaxies and clusters. Our world model sketched above predicts the abundance of galaxy clusters as a function of redshift, which can be compared with the observed

cluster counts. This comparison can then be used to determine cosmological parameters.

Another essential conclusion from the smallness of the CMB anisotropies is the existence of dark matter on cosmic scales. The major fraction of cosmic matter is dark matter. The baryonic contribution to the matter density is  $\lesssim 20\%$  and to the total energy density  $\lesssim 5\%$ . The energy density of the Universe is dominated by the vacuum energy.

Unfortunately, the spatial distribution of dark matter on large scales is not directly observable. We only observe galaxies or, more precisely, their stars and gas. One might expect that galaxies would be located preferentially where the dark matter density is high. However, it is by no means clear that local fluctuations of the galaxy number density are strictly proportional to the density of dark matter. The relation between the dark and luminous matter distributions is currently only approximately understood.

Eventually, this relation has to result from a detailed understanding of galaxy formation and evolution. Locations with a high density of dark matter can support the formation of galaxies. Thus we will have to examine how galaxies form and why there are different kinds of galaxies. In other words, what decides whether a forming galaxy will become an elliptical or a spiral? This question has not been definitively answered yet, but it is supposed that ellipticals can form only by the merging of galaxies. Indeed, the standard model of the Universe predicts that small galaxies will form first; larger galaxies will be formed later through the ongoing merger of smaller ones.

The evolution of galaxies can actually be observed directly. Galaxies at high redshift (i.e., cosmologically young galaxies) are in general smaller and bluer, and the star-formation rate was significantly higher in the earlier Universe than it is today. The change in the mean color of galaxies as a function of redshift can be understood as a combination of changes in the star formation processes and an aging of the stellar population.

### 1.2.8 Cosmology as a Triumph of the Human Mind

Cosmology, extragalactic astronomy, and astrophysics as a whole are a heroic undertaking of the human mind and a triumph of physics. To understand the Universe we



apply physical laws that were found empirically under completely different circumstances. All the known laws of physics were derived “today” and, except for General Relativity, are based on experiments on a laboratory scale or, at most, on observations in the Solar System, such as Kepler’s laws which formed the foundation for the Newtonian theory of gravitation. Is there any a priori reason to assume that these laws are also valid in other regions of the Universe or at completely different times? However, this is apparently indeed the case: nuclear reactions in the early Universe seem to obey the same laws of strong interaction that are measured today in our laboratories, since otherwise the prediction of a 25% mass fraction of helium would not be possible. Quantum mechanics, describing the wavelengths of atomic transitions, also seems to be valid at very large distances – since even the most distant objects show emission lines in their spectra with frequency ratios (which are described by the laws of quantum mechanics) identical to those in nearby objects.

By far the greatest achievement is General Relativity. It was originally formulated by Albert Einstein since his Special Theory of Relativity did not allow him to incorporate Newtonian gravitation. No empirical findings were known at that time (1915) which would not have been explained by the Newtonian theory of gravity. Nevertheless, Einstein developed a totally new theory of gravitation for purely theoretical reasons. The first success of this theory was the correct description of the gravitational deflection of light by the Sun, measured in 1919, and of the perihelion rotation of Mercury.<sup>9</sup> His theory permits a description of the expanding Universe, which became necessary after Hubble’s discovery in 1928. Only with the help of this theory can we reconstruct the history of the Universe back into the past. Today this history seems to be well understood up to the time when the Universe was about  $10^{-6}$  s old and had a temperature of about  $10^{13}$  K. Particle physics models allow an extrapolation to even earlier epochs.

The cosmological predictions discussed above are based on General Relativity describing an expanding Universe, therefore providing a test of Einstein’s theory. On the other hand, General Relativity also describes much smaller systems and with much stronger gravita-

tional fields, such as neutron stars and black holes. With the discovery of a binary system consisting of two neutron stars, the binary pulsar PSR 1913+16, in the last  $\sim 25$  years very accurate tests of General Relativity have become possible. For example, the observed perihelion rotation in this binary system and the shrinking of the binary orbit over time due to the radiation of energy by gravitational waves is very accurately described by General Relativity. Together, General Relativity has been successfully tested on length-scales from  $10^{11}$  cm (the characteristic scale of the binary pulsar) to  $10^{28}$  cm (the size of the visible Universe), that is over more than  $10^{17}$  orders of magnitude – an impressive result indeed!

### 1.3 The Tools of Extragalactic Astronomy

Extragalactic sources – galaxies, quasars, clusters of galaxies – are at large distances. This means that in general they appear to be faint even if they are intrinsically luminous. They are also seen to have a very small angular size despite their possibly large linear extent. In fact, just three extragalactic sources are visible to the naked eye: the Andromeda galaxy (M31) and the Large and Small Magellanic Clouds. Thus for extragalactic astronomy, telescopes are needed that have large apertures (photon collecting area) and a high angular resolution. This applies to all wavebands, from radio astronomy to gamma ray astronomy.

The properties of astronomical telescopes and their instruments can be judged by different criteria, and we will briefly describe the most important ones. The *sensitivity* specifies how dim a source can be and still be observable in a given integration time. The sensitivity depends on the aperture of the telescope as well as on the efficiency of the instrument and the sensitivity of the detector. The sensitivity of optical telescopes, for instance, was increased by a large factor when CCDs replaced photographic plates as detectors in the early 1980s. The sensitivity also depends on the sky background, i.e., the brightness of the sky caused by non-astronomical sources. Artificial light in inhabited regions has forced optical telescopes to retreat into more and more remote areas of the world where *light pollution* is minimized. Radio astronomers have similar problems caused by radio emission from the telecommunication infrastructure

<sup>9</sup>This was already known in 1915, but it was not clear whether it might not have any other explanation, e.g., a quadrupole moment of the mass distribution of the Sun.



<http://www.springer.com/978-3-540-33174-2>

Extragalactic Astronomy and Cosmology

An Introduction

Schneider, P.

2006, XIV, 459 p., Hardcover

ISBN: 978-3-540-33174-2