Chapter 1
Introduction

1.1 The Relevance of Very Distant Galaxies

From observations of the Cosmic Microwave Background (e.g., [491]) and from other, independent astronomical observations we know that, averaged over sufficiently large scales, our universe is highly homogeneous and isotropic. This means that at a given instant of cosmic time our universe shows the same basic properties everywhere, regardless of the distance and regardless of the direction in which we observe. Therefore, at first glance, it may not appear worthwhile to observe distant objects. However, due to the finite velocity of light, a look at distant objects is automatically a look into the past. In astronomy we never see an object in its present state. We always observe the properties which the object had a long time ago, when the light was emitted. Since we know very well that our universe is evolving with time, observations of distant astronomical objects allow us to study the history of our cosmos. In the light of the most distant objects we directly see the universe in its earliest stages of development. Thus, distant objects are interesting not because of their distance in space, but because of their distance in time.

Although during the last decades our understanding of the large-scale properties of the universe has progressed significantly, we still do not know whether the cosmos has a finite volume or whether it extends to infinity. But we know that its extent is much larger than the volume and the distance which we can overlook (cf. Sect. 3.1). The finite size of the observable volume results from the fact that our cosmos has a finite age (of 13.7 billion years) and that light and other information can only reach us from distances for which the light travel time has been smaller than the age of the universe. As a matter of fact, the distance from which we can receive light is even smaller, since during the first 380 000 years Thomson scattering by the free electrons of the hot cosmic plasma made the cosmos opaque. Only when the electrons in the expanding and cooling plasma recombined with the atomic nuclei, the radiation field decoupled from the matter and the cosmos became transparent for most wavelengths. Obviously, only light emitted after this epoch (i.e., only light which was emitted after the cosmos had reached an age of about 380 000 years) can reach us. This includes the photons which were emitted by the recombining plasma itself. At the epoch when the cosmos became transparent, the plasma had a

I. Appenzeller, *High-Redshift Galaxies*, Astronomy and Astrophysics Library,
DOI 10.1007/978-3-540-75824-2_1,

temperature of about 3×10^3 K. Thus, mainly visual and near-infrared photons were emitted by the plasma. But due to their redshift of $z \approx 10^3$ these photons today are observed as the Cosmic Microwave Background (CMB), which was discovered in 1965 [408] at radio wavelengths.

Since the plasma emitting the CMB is the most distant source from which light can reach us, in the light of the CMB we directly overlook the whole cosmic volume which in principle can be observed with astronomical techniques. For all other types of astronomical objects the volume which we can overlook is smaller. There are two reasons for this: Firstly, all other known astronomical objects were formed at later epochs. Thus, their light was emitted later and at a smaller distance from us. Secondly, for many types of objects the most distant existing examples are too faint to be detectable with present technologies. Only a few types of intrinsically very bright sources can be observed at practically all distances where they are expected to exist. Among these intrinsically very bright sources, where we have a complete overview of the total volume where they theoretically can be observed, are the most luminous quasars. Using absorption features which they produce in the spectra of luminous quasars, intergalactic gas clouds and the gaseous disks of gas-rich galaxies can be studied in practically the same volume. Our possibilities of observing the most distant galaxies are somewhat more restricted. As pointed out in the following chapters, we are very close to observing luminous galaxies up to the distance corresponding to the epoch where the first of these objects have been formed. However, galaxies (probably) formed earlier than the luminous quasars, and (as will be explained later) the first (and thus most distant) galaxies were relatively small and faint systems. Therefore, their detection is technically more demanding than observing distant quasars.

In light of the CMB we see a universe consisting of an almost homogeneous hydrogen–helium plasma without heavy chemical elements and with a relative density variation of the visible matter of only about 10^{-5}. Obviously, at this epoch the universe was highly homogeneous on all scales. It was very different from today's structured universe, which contains galaxies, stars, planets, and a multitude of chemical elements, including the heavy elements which are the main constituents of our planet, and of ourselves. This structured and complex universe emerged several hundred million years after the emission of the microwave background when the first stars and galaxies started to form due to the gravitational contraction of the tiny density fluctuations visible in the CMB. The technical progress of the last two decades has made it possible to directly observe this interesting cosmic transition period and to derive, at least in principle, information on the very early galaxies. Obviously, the properties of the early galaxies contain important information of the initial conditions for the formation of the present universe. Moreover, this data is expected to provide constraints on the physical processes in the early universe.

In principle, information on these initial conditions can be derived also from observations of the local universe, since all the properties and the structure observed in our present cosmos have evolved under the laws of physics from these early stages. However, at present there are still large gaps in our knowledge of important constituents of the cosmos (such as the dark energy and the dark matter), and many of the relevant astrophysical processes (such as star formation and galaxy interactions) are not well understood. This makes conclusions based on a backward extrapolation from observations of the present-day evolved universe inaccurate and unreliable. Direct observations of the high-redshift universe are always preferable. Moreover, where extrapolations are unavoidable, observations extending to high redshifts provide a more reliable basis for such extrapolations into the unseen past.

1.2 Space, Time, and Redshift

As pointed out above, observing distant astronomical objects always means observing the past of the universe. The objective of such studies is to obtain information on the history and evolution of our world.

Since the cosmos is not completely homogeneous, there are small local variations of the space curvature, and clocks actually run differently at different locations. However, if the cosmic density is averaged over large scales, the relative density variations become progressively smaller with increasing scale. Thus, on large scales the universe appears homogeneous. Therefore, it is possible to define a mean cosmic time, which (except for regions of very strong gravitational fields) is a good approximation for all reference frames which are locally at rest.

From a variety of astronomical observations we know that our universe is expanding. (A listing and a critical discussion of the evidence for the cosmic expansion can be found, e.g., in [446].) The cosmic expansion means that the distance between objects, which are locally at rest, is increasing steadily. It also means that the wavelength of light is increasing while traveling between two objects which are locally at rest. The ratio between the wavelength of the observed light and the wavelength of the emitted light is equal to the relative change of the linear distance scale, i.e.:

$$\frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_{obs}}{a_{em}} \tag{1.1}$$

where λ_{obs} is the observed wavelength, λ_{em} is the emitted wavelength, and a_{obs}/a_{em} is the ratio between the cosmic scale when the light is observed, and the cosmic scale at the time of the light emission.

In astronomy this wavelength change is usually expressed by the "redshift" z, which is defined as

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}} = \frac{a_{obs}}{a_{em}} - 1 \tag{1.2}$$

For spectral lines, λ_{em} can be determined by means of laboratory measurements or by quantum-mechanical calculations.

In the older astronomical literature, redshifts are often expressed by the product cz (where c is the velocity of light) and are listed in units of km s^{-1} (often without explicitly specifying the units).

The wavelength change actually measured in astronomical spectra differs from the redshift as defined above, since, due to their mutual gravitational attraction and variations of the local mass density and gravitational potential, galaxies normally are moving relative to the local rest frame. Due to the Doppler effect, these local motions (called "peculiar velocities") also produce wavelength shifts, which add to the wavelength shifts due to the cosmic expansion. In order to derive accurate redshifts caused by the cosmic expansion, the measured wavelength shifts have to be corrected for the peculiar velocities of the observed objects (and for the motion of the observer, including the rotation of the Earth, the orbital motion of the Earth, the motion of the solar system in the Galaxy, and the peculiar velocity of the Milky Way galaxy). The effects of the peculiar velocities normally amount to $\Delta\lambda/\lambda \leq 0.01$. Therefore, the relative effect of the peculiar motions are insignificant for large redshifts, but corrections for peculiar motions are very important for nearby objects.

Since the redshift as defined above increases monotonically with distance and with the time which elapsed since the observed light was emitted, in the astronomical literature the dimensionless redshift z is often used as a measure of distances, for characterizing ages, and for defining time intervals. The use of z obviously has the advantage that, at least in principle, z is a directly measurable quantity, and that distances and times expressed in terms of z can be easily compared. However, in practice the correction for peculiar velocities is not always easy or reliable. Moreover, in order to convert z into a linear distance or time units (such as meters, parsecs, seconds, or years)[1] the correct world model and the cosmic parameters have to be known (see Sect. 3.1).

1.3 Historical Remarks

Astronomical observations were among the first scientific activities in the history of mankind. From archaeological evidence we know that systematic observations of the Sun and of the night sky were carried out already during the Stone Age. These early astronomical observations were probably always part of religious ceremonies and divinations. However, their success required the the development of basic scientific methods.

Many prehistoric archeological sites show an exact alignment with respect to astronomical objects or events, indicating that accurate position measurements of celestial objects were achieved already at very early epochs. On the other hand, the development of methods to derive astronomical distances took much longer. Such

[1] The most commonly used unit for measuring astronomical distances is the "parsec" (pc). It is defined as the distance from the Sun at which the semimajor axis of the Earth's orbit has an angular extent of one arcsecond (arcsec). In SI units we have 1 pc $\approx 3.086 \times 10^{16}$ m. Large distances are expressed in kpc, Mpc, and Gpc.

measurements became possible only after the Ancient Greeks found that distances can be determined by measuring angles in a triangle in which the length of one side (the baseline) is known. Using this method, the distance of an object can be derived by measuring the angular difference (called parallax) between the two directions under which the object is observed at the two end points of a known baseline. Since initially all astronomical distances were based on the measurement of such angles, in astronomy the term parallax has become synonymous for the distance itself. Thus, in the astronomical literature, a "parallax" can be an angle (measured in radians or arcsec) or a distance (measured in km or pc).

Among the baselines used for astronomical parallax measurements are known distances on the Earth, the Earth radius, the radius of the Moon's orbit, and the diameter of the Earth's orbit around the Sun. An approximate value for the Earth radius was determined already by Eratosthenes (276–194 BC). Using the Earth radius as a baseline Ptolemy succeeded around AD 150 in measuring the parallax and the distance of the Moon with a relative error $<2\%$. However, the Ancient Greek's attempts to derive the distance of the Sun, using the Moon's orbit as a baseline, resulted in a much too small solar distance. Since the main error source (atmospheric refraction) was not understood until much later, even at the time of Kepler the solar distance and the size of the solar system were still not well known. Only later in the 17th century the correct order of magnitude of the distance to the Sun could be established by Wendelin, who in 1650 derived a value which was correct within a factor of two.

It took almost another two centuries before Bessel in 1837, using the Earth's orbit as a baseline, succeeded in deriving the parallax of a star (61 Cyg). This first distance to an object outside the solar system and accurate lower limits for distances to other galactic stars also provided a first indication of the size of the Milky Way galaxy.

That the visible universe extends beyond the Milky Way galaxy, was not yet clear at that time. Since the invention of the telescope, spiral galaxies had been observed and investigated. That these diffuse objects were outside our Milky Way system and were large stellar systems of their own, had been suggested and discussed since their discovery. But first attempts to measure their distances lead to contradictory results. A reliable confirmation of their extragalactic nature became possible only during the first quarter of the 20th century, when objects of known absolute luminosity (such as bright stars, variable stars, and novae) were observed in the Andromeda nebula and in other Local Group galaxies [117, 239, 240, 322, 389, 473] establishing their large distances.

Among the methods which had been used to derive the distance of the Andromeda nebula was the period-luminosity relation for pulsating stars (see, e.g., [447]). This relation had been found empirically by H. S. Leavitt in 1908 [304, 419] for the δ Cephei variable stars (also called "Cepheids"). Edwin Hubble [239] detected variable stars with the characteristic light curves of Cepheids in the Andromeda nebula. Comparing their observed apparent brightness with the absolute luminosity derived from their pulsation periods and using the period-luminosity relation accepted at that time, he obtained their distances and, thus, the distance of their host galaxy. Soon similar results were obtained for several other nearby extragalactic systems. But with the photographic plates used at that time, it was not possible to observe δ Cephei variables in galaxies that were significantly more distant than Andromeda.

Argum. log Dm		
log Dm	*v*	*n*
0.24	+827 km	9
0.43	+656	7
0.66	+512	8
0.88	+555	10
1.07	+334	5
1.71	− 20	3

Fig. 1.1 Table published by C. Wirtz in 1924 showing the existence of a relation between the mean angular diameter Dm (in arcsec) and the mean redshift of galaxies. The redshifts are expressed as apparent Doppler velocities $v = c\,\Delta\lambda/\lambda = c\,z$ and given in km s^{-1}. Obviously z increases with decreasing mean angular diameter Dm. Wirtz based his table on 42 galaxies, grouped into 6 bins. n is the number of objects in each bin. He correctly concluded that the observed correlation results from an increase of the redshift with distance. However, since no reliable extragalactic distance measures were available in 1924, Wirtz was not able to calibrate his qualitative redshift-distance relation. (Reproduced from [562])

Several years before the physical nature of the spiral nebulae had been clarified, the systematic redshift of their spectra had been found by V. M. Slipher [480]. Using (mainly) Slipher's data C. Wirtz published in 1922 and 1924 two important papers in which he showed that these redshifts were correlated with the apparent total brightness and with the angular diameters of the observed galaxies (Fig. 1.1). Arguing correctly that, on average, the apparent brightness and the angular diameter of galaxies are expected to decrease with distance, he concluded that the observed correlations were due to the existence of a redshift-distance relation for galaxies [561, 562]. Although Wirtz was probably the first one to notice the distance dependence of the galaxy redshifts, he was not able to calibrate this relation, as his distance indicators gave relative distances only. It took another 5 years until Edwin Hubble in his fundamental 1929 paper [241] was able to present a calibrated redshift-distance relation, which today is referred to as the "Hubble diagram" (Fig. 1.2). To derive this diagram Hubble used a sample of about 30 galaxies with known redshifts. For the nearer galaxies in his sample he determined the distance using δ Cephei variables. For the more distant galaxies Hubble used various indirect calibrators, assuming that the distant galaxies had intrinsic properties similar to those found for the nearby galaxies in which Cepheids had been observed.

Since Hubble's (1929) distance estimates contained large systematic errors, the numerical value of the slope of his redshift-distance relation (the "Hubble constant")

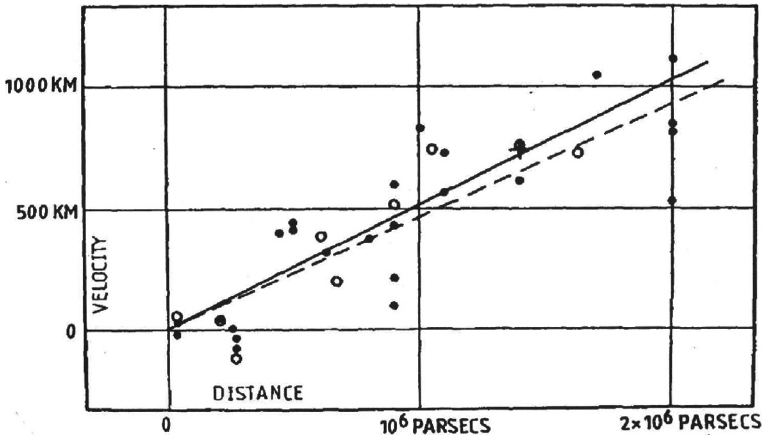

Fig. 1.2 The original Hubble diagram of 1929. The plot gives the observed redshift (again expressed as a Doppler shift in km s^{-1}) as a function of the distance (in parsec). (Reproduced from [241])

was about seven times too large. Consequently, distances derived from the initial Hubble relation were about seven times too small. Thus, the first extragalactic distances were about as inaccurate as the first solar distance derivations by the Ancient Greek astronomers. It took about 30 years to bring the Hubble constant to within a factor two of its correct value, and it took the rest of the 20th century to reduce the relative error to about 10% . (For details of the interesting history of the Hubble constant see, e.g., [508, 525].)

As seen from today, Wirtz and Hubble discovered the expansion of the universe and provided the foundations of present-day cosmological theories. However, neither Wirtz nor Hubble was aware of this discovery. Both regarded their results as support for W. de Sitter's [128] cosmological model, which assumed a non-expanding, static world, where a galaxy redshift results from a distance-dependent time. Although expanding world models based on Einstein's theory of general relativity had been developed by A. A. Friedmann [181, 182] already in 1922, it took much time before the astronomical community took note of these models. Like Einstein and de Sitter almost everybody was still convinced that the universe was static. Even after additional measurements had shown that the observed redshift-distance relation was quantitatively incompatible with the prediction of de Sitter's model, the expanding Friedmann-Lemaître Big-Bang world models found little acceptance in the scientific community. Other cosmological models, such as "tired light" theories and the Steady State cosmology were initially much more popular. Only during the second half of 20th century it became almost generally accepted that we live in a universe which is expanding according to Friedmann's solutions of Einstein's equations.

Although its initial calibration was rather inaccurate and although its physical basis was unclear, Hubble's relation immediately became the most important tool for estimating extragalactic distances. But many astronomers were well aware of the uncertainties of the calibration of the redshift-distance relation. Moreover, the cosmic redshift-distance relation is linear only for small distances. For larger redshifts a conversion of the measured redshifts into distances requires the knowledge of the expansion law and the cosmic parameters. But independent of the calibration problem, redshifts provide at least a reliable relative measure of large distances.

The galaxies in Hubble's 1929 sample all had redshifts $z < 0.004$. But already during the year of Hubble's important publication Humason and Pease observed a galaxy redshift as large as $z = 0.026$ [243]. Two years later the record stood at $z \approx 0.066$. In 1949, after the Mt. Palomar 200-inch telescope had become operational, the high-redshift frontier was pushed to $z \approx 0.203$. During the following years progress slowed down since the low surface brightness of galaxies with higher redshifts (see Sect. 3.1.5) made it difficult to obtain spectra of such objects on photographic plates. By 1960 the radio galaxy 3C295 ($z = 0.462$) observed by Minkowski [355] became the most distant object known. During the following four decades radio sources (radio galaxies and quasars) remained the objects with the largest observed redshifts. Although the first quasars, which were discovered in 1963, had moderate redshifts, within the following 2 years quasars with $z > 2.0$ became known. By 1982 many quasars with redshifts >3 had been discovered and the record stood at $z = 3.87$. In 1999 quasars redshifts of 5.0 were reached [166], and today (as a result of the SDSS survey) a significant sample of quasars with redshifts $z > 6$ is known (e.g., [167, 168]).

The first normal galaxy with a very high redshift ($z = 3.215$) was discovered by Djorgovski et al. [140] while looking for Lyα emission objects near the quasar PKS1614+051. During the following years similar detections were reported by Schneider et al. [459], Hu and Cowie [235], and Steidel et al. [499]. These observations were important as they demonstrated that there existed galaxies at these redshifts which were bright enough to be observed and studied with the techniques available. As a result of these early observations, systematic searches were started which, together with a new class of telescopes with apertures of 8–10 m, yielded within a few years large samples of well-identified galaxies with redshifts $2 < z < 6$, thereby opening the field of this book. During the past years galaxies with redshifts of at least $z = 7.6$ (and possibly >9) have been identified (e.g., [68]), while the highest observed QSO redshift stands at $z = 6.4$.

http://www.springer.com/978-3-540-75823-5

High-Redshift Galaxies
Light from the Early Universe
Appenzeller, I.
2009, XIV, 352 p., Hardcover
ISBN: 978-3-540-75823-5