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CONTENTS

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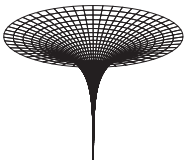
CHAPTER ONE



THE BASICS

1.1 The Size of the Universe

HOW BIG IS THE UNIVERSE? IT IS REALLY, REALLY BIG! MORE seriously, this is a deep question. Addressing it will take us to the heart of cosmology. However, before we get to what the question even means, let us first consider some typical distances. In cosmology, distances are truly vast. To set the scale we will start locally and then work our way out. The Moon is about 250,000 miles away and is considered nearby. Its distance is close to the typical mileage on a car before it breaks down. With a really good car you could imagine driving to the Moon and possibly even making it back. However, if we go beyond the Moon, it becomes cumbersome to keep measuring distances in miles. Because the universe is so vast, we typically measure distances another way—with light. We can ask how long it takes light to travel from an object to us. Since the speed of light is a constant of Nature, it is a

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convenient standard. In one second light travels 186,000 miles. Put another way, one light-second is the distance light travels in one second (186,000 miles). Similarly, in 1.3 seconds, light travels 250,000 miles. Now, instead of specifying miles, we can say the Moon is 1.3 light-seconds away. Note that we are using a time-like term (light-seconds) to talk about distance.

The Sun is on average about 93 million miles from us, or about eight light-minutes away.[1] Because the fastest speed at which information can travel is the speed of light, when something happens on the surface of the Sun we must wait about eight minutes for the light from the event to reach our eyes. We will revisit this concept, applied to the cosmic scale. For now, though, we will focus on distances and not on the time it takes to travel that distance.

The next time you are away from city lights on a moonless night and look up at the night sky, you will see a swath that is brighter than everything else. This glow comes from billions of stars that are part of the Milky Way, our galaxy, of which our Sun is a fairly typical star. A typical galaxy contains roughly one hundred billion stars. One way to connect with this number is that our brains have about one hundred billion neurons; so, there is a neuron in your brain for every star in our galaxy.

The stars in the Milky Way are collected in a sort of disc shape that is about 100,000 light-years in diameter and has a bulge in the middle. Figure 1.1 shows a sketch of how it might appear if we could view the Milky Way from a distance. The galactic plane is an imaginary surface that cuts the disc in half as though you were slicing a hole-less bagel. The solar system

1 The distance of 93 million miles divided by 186,000 miles per second is 500 seconds, or a little more than eight minutes.

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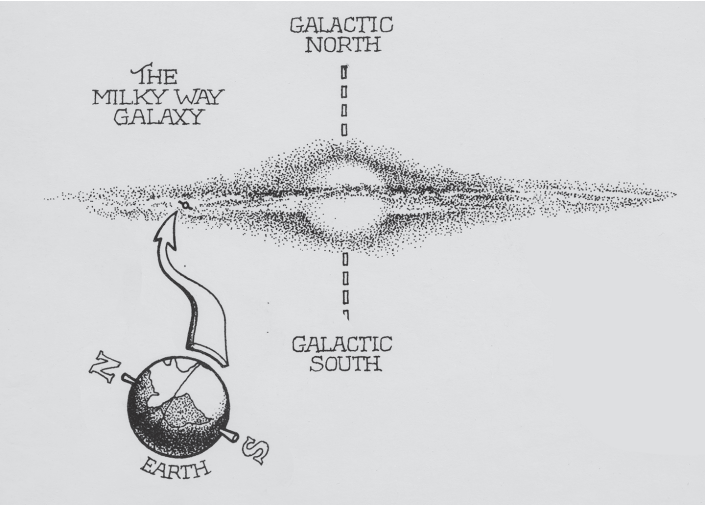

FIGURE 1.1. The Milky Way as seen by an imaginary viewer at a distance. The overall shape resembles a disc with a bulge in the middle. The galactic center is at the middle of the bulge. The orientation of the Earth with respect to the galaxy is approximate. *Credit:* Stewart Brand and Jim Peebles in The CoEvolution Quarterly.

is about halfway out from the center of the disc. When we look toward the center of the disc, we see many more stars than when we look well off to the side. It is a bit like living on the outskirts of a city. You are a part of the city, but you can still see all of the tall buildings off in one direction.

Plate 2 is a picture of the Milky Way, taken with a CCD camera using visible light.[2] If our eyes were more sensitive

2 Our eyes detect the spectrum of colors that make up visible light, each color corresponding to a different wavelength. A typical visible wavelength is about one hundredth the thickness of a human hair. More formally, a this typical wavelength is 0.5 microns, where one micron is a thousandth of a millimeter . There are many other possible wavelengths of light that we cannot see. Taken together, these are called the "electromagnetic spectrum," as shown in appendix A.1.

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and larger, we would see the galaxy like this. The dark swaths in this image come from dust in our galaxy that obscures the starlight, somewhat like smoke obscuring flames from a fire. In cosmology, "dust" refers to microscopic particles comprised of a variety of materials including carbon, oxygen, and silicon. Plate 3 shows a different view of the Milky Way, this one made by the Diffuse InfraRed Background Explorer (DIRBE), an infrared telescope and one of the three instruments on the COsmic Background Explorer (COBE), satellite.[3] Unlike the image in plate 2, this was made at "far-infrared" wavelengths, in particular at 100 microns. Infrared radiation tells us how things emit heat. In this image we see primarily the thermal glow of the Milky Way, in other words, the emission of heat. The heat comes from the dust that fills our galaxy, the same dust that obscures the starlight.

A typical galaxy like the Milky Way has an average temperature of about 30 K, so it is not very hot but it still emits thermal energy. We can draw a loose analogy with an incandescent lightbulb. The bulb is most obvious to us because of the visible light it emits, analogous to the light in plate 2. However, the lightbulb produces much more energy as heat that we can feel but cannot see.[4] When you touch an incandescent bulb it is hot. You may have seen pictures of houses taken in infrared light. These pictures tell you where the heat is leaking out

3 The other two instruments discovered the anisotropy in the CMB (DMR, the Differential Microwave Radiometer, leader George Smoot) and made the definitive measurement of CMB temperature (FIRAS, the Far InfraRed Absolute Spectrophotometer, leader John Mather). Mike Hauser led DIRBE. The instrument is best known for detecting the combined thermal emission of all the galaxies in the universe.

4 Modern LED or CFBs have a higher ratio of visible light to heat, which is why they are more efficient for lighting.

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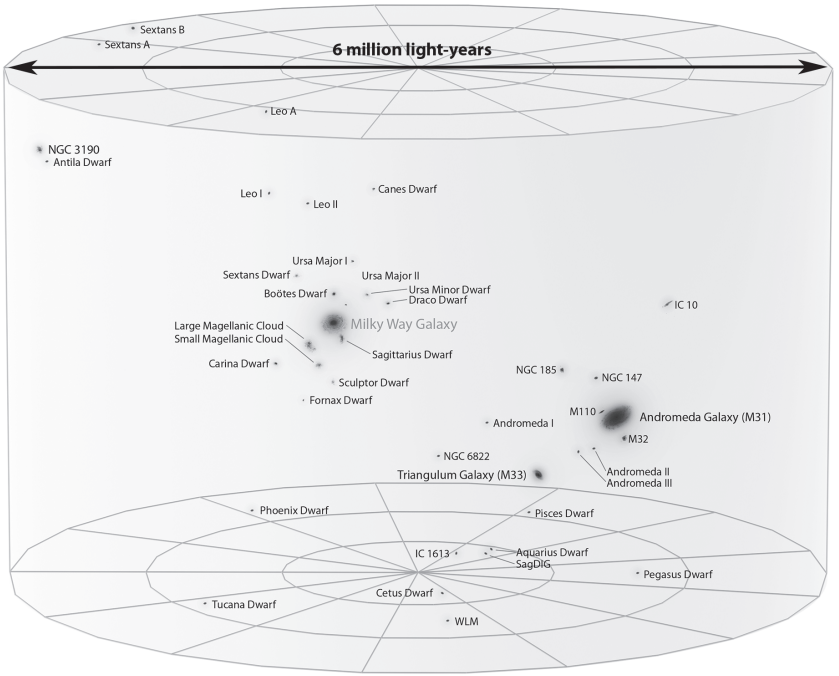

FIGURE 1.2. The Local Group of galaxies. Andromeda is about 2.5 million light-years away but can be seen with the naked eye in dark conditions away from city lights. In length it appears a few times as large as the full moon. The Magellanic Clouds are readily visible by eye in the southern hemisphere. The larger one, close to the Milky Way in this image and shown in plate 3 emitting thermal radiation, is about twenty full moons across. The top and bottom wire grid "wheels" are six million light-years in diameter. *Credit:* Andrew Z. Colvin, https://en.wikipedia.org/wiki/Local_Group. Need formal permission.

(often at the windows). When you feel the heat from a hot body, it is mostly infrared radiation that you sense.

Let's take another step out into the cosmos. Our galaxy is a member of the "Local Group" of roughly 50 galaxies, as shown in figure 1.2. The Local Group is some six million

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light-years across. In this collection, the Milky Way is second in size to the Andromeda galaxy but the range of sizes is quite large. Whereas Andromeda has about a 1,000 billion stars, the smaller "dwarf" galaxies have tens of millions of stars. The Large Magellanic Cloud (plate 3 & figure 1.2) is a nearby small galaxy that orbits the Milky Way.[5] With galaxies orbiting galaxies the distances are already quite large but, as the name implies, these galaxies are still "local." Although there is no sharp boundary for when something is said to be "cosmological," we typically think in terms of spheres or cubes about 25 million light-years across. The Local Group is just a fraction of this size.

Plate 4 is an amazing image, taken with the Hubble Space Telescope by observing in one direction for almost 300 hours in order to build up sensitivity to the light emitted from faint objects. The image, known as the Hubble Ultra Deep Field, is somewhat akin to a super-long camera exposure. The most distant objects in it are billions of light-years away. The area covered by the image is about a sixtieth the area of the full moon. We can be a bit more quantitative. The angular width of the full moon is about one-half a degree across, or roughly half the size in angle of your little finger when held up at arms length.[6] You can compute that it takes 200,000 full moons to cover the full sky. Here is the mind-blowing thing about the image: only a handful of the objects in it are stars—the large

5 Although named after Ferdinand Magellan's report of them in 1519, they were first recorded more than 500 years earlier by Abd al-Rahman al-Sufi Shirazi, a Persian astronomer.

6 If you lined up full moons side by side, it would take 720 to make a circle that went through both the north and south celestial poles (or any great circle) because there are 360 degrees in a circle. The conventional notation is that the Moon is 0.5° in diameter, or, in our example, 360°/720.

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majority of objects are *galaxies*. And each of those galaxies typically includes about 100 billion stars.

To determine the number of galaxies in the image, you simply need to count them. With a full-resolution picture you could do this by hand, but it is easier to use computers. The Hubble Ultra Deep Field team finds about 10,000 galaxies in the image, which means that across the full sky there are about 100 billion galaxies.[7] To emphasize, we *observe* that there are a *finite* number of typically sized galaxies. We say that in the *observable universe*, the subset of the whole universe that is observable by us in principle, there are roughly 100 billion galaxies, each typically with about 100 billion stars. It is a coincidence that the numbers are so close.

We have just introduced a profound concept, that of the "observable universe," and a profound observation, that in the Hubble Ultra Deep Field we have observed essentially all the Milky Way type galaxies that can be seen in that direction. In other words, with the Hubble Ultra Deep Field we have gone as far as we can in counting objects. To understand these ideas, we will have to consider a universe that evolves with time, as we do below, but first we want to continue to think of the universe as an endless and static expanse that we can explore at will.

If we could freeze time and tour the universe, what would we see? Let's put aside the finite speed of light and imagine that someone, say Alice, could go anywhere in the universe instantaneously and communicate with someone else

7 This is [10,000 galaxies per Hubble Ultra Deep Field]×[60 Deep Fields per full Moon]×[200,000 full Moons in the full sky]=120,000,000,000 which we round down to 100 billion. If we looked at much lower mass galaxies than are readily seen with the Hubble, we might get a factor of 10 more, but each would have far fewer stars.

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instantaneously. We can think of galaxies as cosmic signposts. We can, in principle, give them names and know where they are in the universe. As you can see in the image of the Local Group in figure 1.2, this accounting has already been done locally. But we want to go to much greater distances. Let's say Alice is in a distant galaxy that is ten billion light-years away. We ask her to describe the local cosmic environment in broad terms, such as the number and general appearance of the other galaxies near her. We then compare our description from our home in the Milky Way to Alice's. We find the descriptions are similar. Although there would be a large variety of galaxies, no matter where we went, no matter how far away, no matter what direction, on average the galactic environment would look very much like it does right around us, and the same laws of physics would describe Nature.

This is an important conceptual point and is worth repeating because we will build on it. At this instant in time, every place in the universe looks, in broad brush strokes, similar. We could call up someone near any distant galaxy and ask them to describe the galaxies within a 25 million light-year diameter sphere centered on them. We would find that their general description also described our galactic neighborhood.

The idea that the universe is on average the same everywhere you go at a specific time is called Einstein's "cosmological principle." When a quantity is similar everywhere in space, it is said to be *homogeneous*. The cosmological principle thus says that the universe is homogeneous when averaged over a large enough volume. The cosmological principle also says that on average, the universe looks the same in each direction. This property is called *isotropy.* It means that on average the picture from the Hubble Ultra Deep Field would look the

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same regardless of the direction we pointed the satellite as long as we looked away from nearby objects like the galactic plane. Our universe is homogeneous and isotropic no matter where we are in it.

The concepts of homogeneity and isotropy are related but distinct. For example, if your universe were a grapefruit and you lived at its center, you'd say your cosmology was isotropic (ignoring the membranes around the pulp), but because the pulp is in the middle and the rind is on the outside, you would say it is not homogeneous. It took a conceptual advance to postulate the cosmological principle. In our day-to-day lives the sky is far from isotropic: we see the Sun rise and set, and the solar system is far from homogeneous as the planets lie roughly in a plane. To think about the universe, we need to step away and imagine a much more simple distribution of matter on a much, much larger scale.

We have completed a whirlwind tour of the universe. We stepped out to greater and greater distances until, with the Hubble Ultra Deep Field, we ran out of objects to observe. To understand how this can happen, we will need to consider the evolution of the universe in time, which we do in the following sections. That aside, limiting ourselves to a purely spatial description, we got out far enough to envision a homogeneous universe frozen in time and full of galaxies, on average, like the ones around us. At this instant, we can think of the universe as an endless three-dimensional grid of Tinkertoys with the hubs representing collections of galaxies that look in general like the ones around us. Of course, the galaxies are distributed throughout space and not on a grid pattern, but the Tinkertoys help us imagine a coordinate system for describing the cosmos.

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1.2 The Expanding Universe

In the last section we imagined the universe as static, but it is not: the universe is expanding. This is not a theory, or a model—it is an observational fact. Once we get well past the Local Group (figure 1.2) and out to cosmological distances, we observe that *the farther away a galaxy is, the faster it is moving away from us.* This is called the Hubble-Lemaître Law, after Georges Lemaître who, based on observations available at the time, published it in an obscure journal in 1927, and Edwin Hubble, who published it independently in 1929. In day-to-day terms, the Hubble-Lemaître law states that for every million light-years away you observe an object, its recessional speed increases by about 15 miles per second. This value is called "Hubble's constant."[8]

Hubble's observation immediately brings to mind the question: Are we at the center of the universe? The answer is no. Just because we see all galaxies rushing away from us, it does not mean that we are at the center of the universe. We are special but not *that* special. All observers on all galaxies anywhere in the observable universe see the same thing. This is because the expansion has a particular form, namely that the recessional speed is proportional to the distance. That is, if a galaxy is twice as far away, it is moving away from us twice as fast. Let's be more concrete and imagine a sample string of galaxies each representing their local region of 25 million

8 Hubble's original value, which was based on his observations of distances and velocities measured by Vesto Slipher, was about seven times the currently accepted value because of a flawed distance estimator. The history of the discovery, like so many, is complex and involved many others, including Hubble's assistant, Milton Humason. The value used in the scientific literature is 70 km/s per Mpc. This corresponds to 15 miles/sec per million light-years distance to somewhat less than 15% accuracy.

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light-years across. We will start with the Milky Way in the center. If the galaxy named "Nan" was 25 million light-years away, it would be moving away at 375 miles per second according to the value of Hubble's constant ([15 miles/sec per million light-years]×[25 million light-years] = 375 miles per second). If another galaxy named "Orr" was 50 million light-years away, it would be moving away at 750 miles per second, and if "Pam" was 75 million light-years distant, it would be receding at 1125 miles per second. These are depicted in a row in the top panel of figure 1.3. Even with these enormous distances, the speeds are less than 1% the speed of light.

Now imagine that you could be instantly transported from the Milky Way, in the center of figure 1.3, to Nan. That is, you would be at rest on Nan. Of course, if you looked back at the Milky Way while sitting on Nan, it would be moving away from you at 375 miles per second. Here is a way to think about how the whole picture changes. If you were on the Milky Way and wanted to be at rest with respect to Nan, you would need to move at 375 miles per second to the right. This is shown in the middle frame. Moving next to something with the same speed it has is the same as being at rest with respect to it. This is just like looking at a car next to you on the highway going the same speed. Relative to you, that car is stationary. In the bottom illustration, we have just subtracted the velocities[9] to see what the universe looks like from the perspective of someone on Nan. But now note that the bottom picture looks just the same as the top but from the perspective of someone on Nan. Here again, the same Hubble-Lemaître law applies. Someone on Nan suspects they

9 A velocity is a speed with a direction associated with it. To subtract velocities, take the arrows in the middle, reverse their directions, and add them to the top row.

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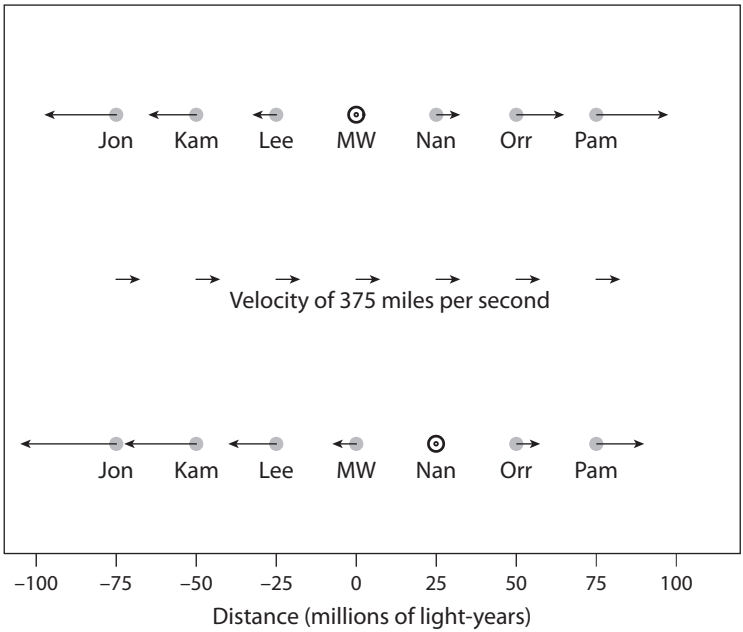

FIGURE 1.3. The expansion of the universe in one dimension. The top row shows the expansion from our point of view. The "MW" stands for the Milky Way. The circle indicates that it is reference point. The arrows indicate velocity. The galaxy Nan, at 25 million light-years' distance, is moving away from the Milky Way at 375 miles per second. Since Orr is twice as far away as Nan, it is moving away twice as fast as indicated by the velocity arrow being twice as long. The middle row shows the speed of Nan, but at all points in space, not just at Nan's location. Say you were moving at this velocity and near Nan. To you it would seem as though Nan was standing still. The bottom row shows the pattern of velocities from the point of view of someone standing on Nan. The circle shows Nan is now the reference. As you can see an observer on Nan seems to be the center of the universe and all the other galaxies are rushing away and obeying the same Hubble-Lemaître law.

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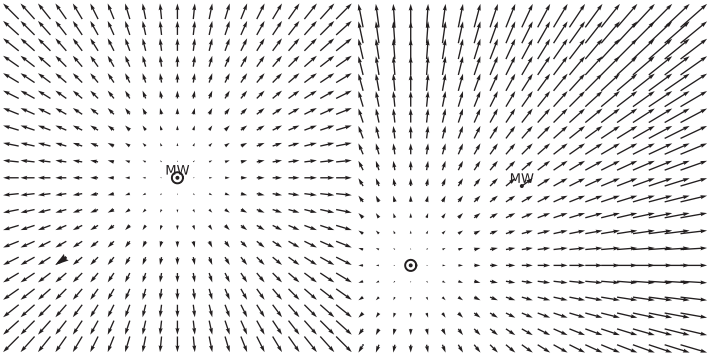

FIGURE 1.4. The expansion of the universe but now in two dimensions. Each point represents a galaxy. The arrows show the velocity the galaxy is moving as we see it. Of course, in reality the galaxies are much more irregularly spaced. The left side shows what we'd see looking out to greater distances than in the previous figure. The circle around the Milky Way indicates that it is the reference. Again, it looks like the galaxies are all moving away from us in proportion to their distance. Imagine that instead we transport ourselves to the galaxy marked by the thick arrow four galaxies in and six up from the lower left and so that we are at rest with respect to it. The right shows the velocities with this new galaxy as the reference. The overall picture is the same: we seem to be at the center with all other galaxies rushing away from us with speeds proportional to their distance.

might be at the center of the universe. For the time being, just imagine that this line of galaxies can go on forever and that the velocities increase without limit.

The main point here is that as long as the speed of recession is proportional to distance, all observers in the universe see the same pattern of recession and to all it *appears* that they are in the center of the expansion. Although we have shown the expansion with a line of galaxies in one dimension, it works in two and three dimensions as well. In figure 1.4 you can see the same process in two dimensions from the perspective of two widely separated galaxies.

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There is a simple and yet radically different way of thinking about the expansion. In the picture we just gave, we had in our minds a fixed space in which the galaxies were moving. That is, the *space* was fixed and the galaxies were traveling through it at different velocities. We now want to make a huge conceptual jump. Let us again imagine that the galaxies are on a line as in the top row of figure 1.3, but let's ignore the velocity arrows. Think of the galaxies as representing coordinates in space, just like mile markers on a highway (in one dimension) or as latitude and longitude positions on a two-dimensional map. Instead we want to add space between the mile markers. In the top row, this is equivalent to taking a pair of scissors, cutting the figure vertically between all galaxies, and taping an extra strip of paper of width, say, 0.2 cm wide. Let's say it takes us 30 minutes to complete this process. After we are done, Nan is 0.2 cm farther from the Milky Way than it initially was, Orr is 0.4 cm farther away than initially, and Pam is 0.6 cm more distant than initially. In this 30 minutes, Pam has moved three times as far as Nan, and Orr has moved twice as far as Nan. Pam, who started out three times farther than Nan, has moved three times as far in the same 30 minutes and thus *apparently* has three times the speed. We have reproduced the cosmic expansion but from a completely new perspective. Instead of space being fixed with the galaxies moving, the space between the galaxies is expanding.

From now on we want to think of space as fungible, not as a set stage on which the cosmic evolution unfolds but rather as the entity that is evolving.[10] In the above, Jon, Nan, and

10 For the experts, what we term "expanding space" is increasing the scale factor $a(t)$ in the metric. There are heated discussions about whether "expanding space" is a useful concept. In appendix A.2 we discuss some of the pitfalls.

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Pam don't have to communicate with each other. They just sit still while space is created locally everywhere at the same time and at the same rate. In this picture, the Hubble-Lemaître law is just a statement about a specific rate of the expansion of space. In the two-dimensional case shown in figure 1.4, we cannot cut strips of paper but instead can imagine the galaxies as painted dots on a rubber sheet. Here, expanding space would be like stretching a very, very large rubber sheet in both dimensions. In three dimensions, we can again imagine an endless grid of Tinkertoys with the wooden hubs as the fixed coordinates and the struts between the hubs as the space that grows with time.

Although we have introduced a few analogies—making space by adding strips of paper, an expanding rubber sheet, Tinkertoys with growing links—we need to keep in mind that these are just analogies for describing the mathematical structure of general relativity. In space, there is nothing that acts like paper, rubber, or wood, but these different analogies are useful for different situations. The theory is more subtle and deep than we can convey with simple models and everyday objects.

To reiterate, though, we can think about the expansion of the universe as the expansion of space. The rate of expansion depends on the rate at which we "make space." We should *not* think about the expansion of the universe as galaxies flying away from each other in a pre-defined space. The Big Bang was *not* like a bomb exploding billions of years ago. The Big Bang marked the beginning of an explosion of space, everywhere at a fixed time in our distant past.

To recap, we started off this section by explaining the Hubble-Lemaître law and showed that no matter where you are in the

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universe, you appear to be in the center with the speed of recession of other galaxies proportional to their distances. We then introduced space as the changing quantity, and realized that if the galaxies represent fixed coordinates, the Hubble-Lemaître Law describes space expanding at a specific rate. In general we can expand space at any rate and still not be in a special place. We continue to think of the universe as infinite in extent.

Our new way of thinking about space begs the question "What is space?" This is a deep question, akin to "What is a vacuum?" Most physicists would say that we do not know. There are epochs in our cosmic history when an expanding space is the best description of Nature, and there are epochs when it can be misleading, leading us to imagine forces that do not exist. Regardless, an expanding space is a unifying concept that helps us envision the expansion of the universe and dovetails nicely with the warping of spacetime described by general relativity. We consider other elements of expanding space in appendix A.2.

Before moving on, we note that on human scales the expansion is ignorable. We see it only because we can look out to such vast distances. The forces that hold the Earth together and that bind the Earth to the Sun completely dominate the effects of an expanding space. Even our galaxy is not expanding. Gravity binds it together. We can be more quantitative. In 100 years, the width of this page would expand by about 0.001 microns, or roughly ten times the diameter of an atom if it partook in the cosmic expansion. This would be measurable. However, the forces that bind the molecules in the paper, which by measurement appear to be constant in time, would keep the page at its current size.

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1.3 The Age of the Universe

If the galaxies are all apparently moving away from us now, they were closer together in the past. The universe used to be more compact: those galaxies in the Hubble Ultra Deep Field were ever closer together as we go back in time. To be specific, we will use the term "compact" to mean smaller in length or distance as opposed to volume. If the diameter of a sphere were halved, we would say it is twice as compact even though its volume would decrease by a factor of eight. When the universe was twice as compact, the objects in it were half as far away from each other.

At some point in the distant past, the galaxies were much, much closer together. If we go back even earlier, the galaxies had not yet formed, and instead of thinking of the space between galaxies, we think of the space between the constituents of galaxies. As we go farther back there was less and less space and, since there is the same amount of matter, the matter *density*[11] becomes enormous. At some point in our extrapolation the currently known laws of physics break down, but we need not extrapolate back that far. The important point is that we can extrapolate back to a time when the universe was extremely dense and that we reach that epoch in a fixed amount of time. In other words, the universe has a finite age.

The most accurate measure of the age of the universe comes from the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellites. The best estimate, taking

11 The matter density is the mass per volume. Similarly, we can have an energy density which is just the energy per volume. Cosmologists freely convert from one to the other using Einstein's celebrated relation, $E = mc^2$ where E is the energy, m is the mass, and c is the speed of light.

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into account everything we know about the expansion history, gives 13.8 billion years to roughly 1% accuracy, that is the age is between 13.7 and 13.9 billion years.

We can get an approximate value of the age of the universe from the observations we explored in the previous section. As we saw, two galaxies 50 million light-years apart are moving apart at 750 miles per second. At this speed, assuming it is constant, 12.5 billion years ago the galaxies were on top of each other. Two galaxies 100 million light-years apart are now moving apart at 1500 miles per second, and so in the same amount of time, they too would be on top of each other,[12] as depicted graphically in figure 1.5. By extension all observers, no matter how far away they are from each other, would say the universe is 12.5 billion years old as all galaxies would be on top of each other when all the space is taken away. It is fortuitous that this simple estimate is so close to the more accurately determined value of 13.8 billion years, as we discuss next.

When we extrapolate back as we just did, we assume the rate of expansion has been constant. However, we know it has *not* been constant. At the very least, because gravity is a purely attractive force, the galaxies will be pulled toward one another, tending to slow the expansion. With just this simple observation we are linking the presence of matter to the rate of expansion, a concept at the heart of general relativity. Since the expansion rate has not been constant, the Hubble constant

12 A speed of 750 miles per second is the same as a distance of 4 million light-years per a time interval of one billion years. The age is then [50 million light-years]/[4 million light-years/ 1 billion years] =12.5 billion years. Similarly, a speed of 1500 miles per second is the same as 8 million light-years per billion years. The age is then [100 million light-years]/[8 million light-years/ 1 billion years] =12.5 billion years. We give three significant digits so you can check the math. Using a more precise value of the Hubble constant would give 14 billion years.

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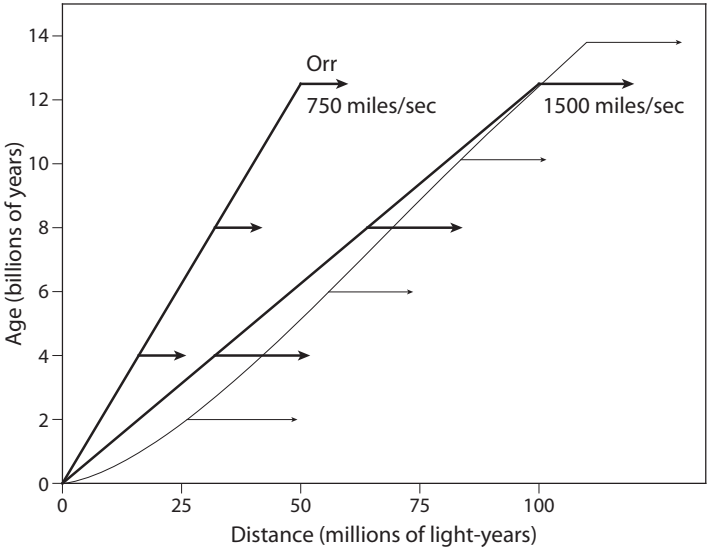

FIGURE 1.5. We imagine ourselves sitting on the *y-axis* at the ages marked there. Galaxy "Orr," as in figure 1.3, is at a distance of 50 million light-years and moving away at 750 miles/sec. Similarly, a galaxy at a distance of 100 million light-years is moving away at 1500 miles/sec. In the approximation that the speed of a galaxy does not change, the thick black lines show that as you go back in time, the galaxies get closer and closer together until they are on top of each other. As you can see, the Hubble "constant" is larger in the past even in this simple approximation. The thin gray line shows the true trajectory of a galaxy that was 100 million light-years away when the universe was 12.5 billion years old.

has not been the same throughout our cosmic history. The actual value depends on cosmic epoch and so it is often called the Hubble "parameter." The value we gave above, 15 miles/sec per million light-years, is only applicable now.

As recently as the 1990s there was no consensus on how to extrapolate back because we did not know the expansion rate throughout the history of the universe. However, as the

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web of observations has become ever tighter, we have learned about the cosmic composition and consequently the expansion history. We are now reasonably confident that through extrapolating back in time we know the age of the universe.

In some models of the universe, the current expansion is just one of many, perhaps one of an infinite number, of expansion cycles. As yet, there are no observations as yet to rule such models in or out. Most cosmologists do not subscribe to the cyclic model because it has not been as widely scrutinized as the baseline "inflation model" which we discuss later. However, we should keep in mind that cyclic models are a possibility. If in fact the universe is cyclic, then the 13.8 billion years would refer to the age of this cycle and the discussion in this book would refer only to the latest cycle.

We now have the framework to be more precise about the term Big Bang. We will take it to mean the time at which the universe began to expand. It is when we start our clocks. The term has nothing to do with space. We do not yet know enough physics to extrapolate all the way back to the Big Bang, even though many cosmologists are working on the problem.

In section 1.1, when we talked about the distance of an object, we imagined the universe as frozen in time. We can now appreciate the reason for this. There is a difference between the distance to an object when the light we observe was emitted and the distance at this instant after accounting for the expansion of the universe. At this instant, the object is farther away than when it emitted the light. Instead of talking about how far away something is, from now on we will mostly talk in terms of the compactness of the universe when the object emitted the light we observe. Equivalently, we can label the object by its age when it emitted the light we observe. By

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referring to compactness and age, we sidestep the fact that the universe expands while light travels to us. We say, then, that the most distant objects in the Hubble Ultra Deep Field emitted their light when the universe was about ten times more compact and 0.4–0.7 billion years old and don't mention distance. We follow the same practice for events and epochs as well as for objects. For example, about 5.9 billion years after the Big Bang, about 8 billion years ago, the universe was twice as compact. Cosmologists use slightly different terminology and say that the "scale factor" is 0.5 because distances between objects when the universe was twice as compact are half (0.5) the current size. For the most part, we'll use compactness, but there are times when the scale factor is easier. For example, the Earth and Moon formed about 9.3 billion years after the Big Bang, or roughly 4.5 billion years ago, at a scale factor of 0.71. Dinosaurs roamed the Earth 0.1 billion years ago when the scale factor was 0.993, and *Homo sapiens* appeared a mere 100,000 years ago when the universe was only negligibly more compact than it is today. Appendix A.3 provides a time line of significant events and the associated cosmic compactness.

In the previous two sections we added the element of time to the static picture we started with in section 1.1. Let's put this in the context of Tinkertoys. We now see that 13.8 billion years ago, all the wooden hubs were on top of each other and smushed together. Since, as far as we are able to tell, the Tinkertoy grid is endless in space today, it is still endless after rolling back the expansion; but, as we do so, the links get increasingly shorter and thus the whole grid structure becomes much more dense. We cannot extrapolate back to infinite density or zero time: we don't know how because

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the laws of physics break down. Although we have learned a lot, the picture is not fully satisfying because we still haven't explained why we can count all the objects in the observable universe in the direction of the Hubble Ultra Deep Field. We tackle that next.

1.4 The Observable Universe

We just saw that the age of the universe is finite and that all observers agree on its value. The next key ingredient for developing our model is taking into account the speed of light. So far, we have primarily used the finite speed of light to establish a distance, namely the light-year. We continue in that vein.

If we could instantaneously travel anywhere in the universe *right now*, the galactic environment would look similar to the environment around us. This is the cosmological principle. There would be a variety of galaxies, but no matter where we went we would compute the age of the universe to be 13.8 billion years.

Because the speed of light is finite and we know the age of the universe, there is an upper limit on the size of the universe we can observe. In other words, the size of the observable universe is finite. It is easy to get an estimate of this size. To a first approximation, in one direction we cannot see farther away than the age of the universe times the speed of light. It is as though each observer is in the middle of a spherical volume with a diameter of $2 \times 13.8 = 27.6$ billion light-years. The actual diameter of the spherical volume is a little more than three times larger because our approximation did not include the fact that the universe expands while light is traversing it.

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Nevertheless, the important conceptual point is that because information cannot travel faster than the speed of light there is a limit to how far we can see, hence the name the "observable universe." When cosmologists talk about the "universe," often they really mean the observable universe. It is good to keep in mind, though, that at this instant, the galactic environment at the "edge" of our observable universe is similar to what we see around us. See appendix A.4 if you'd like additional details on the relation between the age, size, and compactness of the observable universe.

1.5 The Universe Is Infinite?

Far, far beyond our observable universe, space—and even the laws of physics—might be different. We do not know whether the universe is truly infinite, in the sense that it goes on forever in space. However, observations tell us that an infinite universe with properties similar to the cosmic environment around the Milky Way is the best and most parsimonious description of the data. That is, we cannot tell the difference between what we observe and a model of the universe that is infinite in spatial extent.

To put this in context, until a few decades ago there was no scientific reason to believe a priori that the universe was infinite. Cosmologists did not known whether continued observations would tell us that the universe was finite, in other words that it had a finite extent and contained a fixed amount of stuff. If so, we would still have an expanding universe with a finite age, but it would be finite in extent and would collapse in a finite time. Instead, the observations of the contents of the universe, which we describe in the next chapter, have

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told us that for all intents and purposes we should treat the universe as infinite.

For a moment, let's picture the universe as an absolutely enormous container of chocolate chip ice cream. Think of the chocolate chips as the galaxies and the ice cream as the space. Our observable universe would be like a very large scoop taken from somewhere inside the container, far away from the container walls. Our scoop would have all sorts of different sized chips. But all scoops would be similar and recognized as the same chocolate chip ice cream no matter where we took them, as long as they were well away from the walls. The container walls, if they exist, represent some new physics to which we have no access.

The extent of the universe is an active area of investigation. Every now and then someone comes up with a model for a finite universe. However, when the predictions of the model are compared to the data we find that an infinite universe provides a better description of the observations. With this picture in mind, the question "What is the universe expanding into?" is not answerable or even relevant.

1.6 How to Look Back in Time

We now add the next conceptual component to our picture. This one is again based on the speed of light, but here we are not using light as a measure of distance. Earlier we noted that since the Sun is eight light-minutes away, we see it as it was eight minutes ago. Similarly, if an object is 20 million light-years away, when we observe it we see it as it was 20 million years ago. As we peer deeper and deeper into space we see objects as they were at earlier and earlier stages in their lives.

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Our whole cosmic history can be read by looking ever deeper into space, because as we do so we look farther back in time. In other words, telescopes are like time machines.

First let's think about what this means taking just a small step out. Stars can explode, releasing enormous amounts of light and particles in a "supernovae." We are able to see these explosions. In 1987, we saw that a star exploded in the neighboring Large Magellanic Cloud (plates 3 and figure 1.2). The Large Magellanic Cloud is about 160,000 light-years away. That is, the star actually exploded before *Homo sapiens* first came on the scene, but we only saw the light in 1987. This particular supernovae, called 1987A, is unique because in addition to the light, we detected neutrinos from it. Neutrinos are elusive elementary particles associated with nuclear interactions. They can travel at close to the speed of light and they barely interact with matter. We will return to them in more detail later, but for our purposes here, note that it is not just light that comes to us from the distant past but particles as well. From this supernova alone, roughly one hundred billion neutrinos per square centimeter hit the Earth. Most passed right through. Twenty-five were detected by the Kamiokande detector in Japan.

Supernovae are so bright they can be seen to vast distances. With powerful telescopes, astronomers can catch supernovae from relatively short-lived stars that exploded when the universe was twice as compact as it is now, 5.9 billion years after the Big Bang. That means the original star has not existed for 8 billion years! What is left for us to detect is a roughly spherical shell of light and particles traversing the universe. We see this shell as it passes by Earth and as the billions of particles associated with it stream through us as if we didn't exist. Similar supernovae are taking place all over the universe

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and sending out their blast waves to travel the cosmos. For the ones we detect, we can study the dying embers of the explosion to understand the composition of these distant stars.

Although individual young stars at great distances are too small to see unless they explode, we can see nascent galaxies from when the universe was less than a billion years old. Let's go back to the Hubble Ultra Deep Field. Plate 5 shows us what we see as we peer deeper and deeper into space. Through a combination of sensitivity and ability to focus intensely on a small patch of sky, the Hubble and other telescopes can almost look back to a time when galaxies were just forming. Earlier we said that we could count all the galaxies in the universe. Now we can see what this means. We can look back to a time before galaxies existed, which corresponds to an epoch when the universe was about 20 times more compact and about 200 million years old (see appendix A.3). Thus, in the part of the universe to which we have access, our observable universe, we can count *all* the galaxies. Again, there are about 100 billion broadly similar to the Milky Way.

If we peer deeper still we could see the birth of the first stars. This has not yet been done, but instruments are being built to make this possible. Going back even farther in time, we can see the remnant radiation of the Big Bang, the Cosmic Microwave Background. It is the light from the edge of the observable universe.

We have presented a vast and expanding framework with which to think about the universe. The expansion forces us to think about a more compact universe in the past. We extrapolated the expansion all the way back to a dense Big Bang that took place 13.8 billion years ago. This is the age of the universe. The finite speed of light combined with this fixed

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time led us to realize that we can only look so far out into the universe. In other words, we can access only the observable universe.

For much of the preceding discussion, the galaxies were just distance markers or signposts that helped us understand ideas such as "the observable universe" and that our universe has a definite age. We could have developed the same picture with just a small fraction of the galaxies we actually observe. We were, after all, only considering aspects of space and time as linked by the speed of light. But, as we will see, the contents of the universe and the expansion of space are intimately related. As a first step of making the connection, let us turn to the question of what the universe is made.

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INDEX

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