WELCOME TO THE UNIVERSE IN 3D

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PREFACE

Go out and simply look up at the night sky. Everything from the Moon to the planets and stars to the band of the Milky Way appears to be pasted on a two-dimensional surface, the dome of the sky. Yet, over time, humans looking up at the sky (just like you) discovered something fundamental. The universe has depth. By measuring the distances to the objects they observed in the sky, humans began to understand the vast three-dimensional volume of the cosmos. The history of our dawning comprehension of the depths of space is the story of astronomy as a science—the story of humankind's observations and ever-more-accurate measurements of the positions and distances of objects in the universe.

In this book, we will take you on a visual tour of the observable universe—by showing you the universe in depth. We will guide you through a set of spectacular images of the cosmos—of celestial objects and features of the universe that have been observed and measured by astronomers, presented in rough order of their distance from Earth. Each striking image is accompanied by a caption on the facing page, which tells you the story and significance of the image, pointing out interesting features. We begin with the Moon and move outward through planets, stars, and galaxies, finally reaching the cosmic microwave background radiation (CMB), ancient radiation left over from the Big Bang, which is the most distant thing we can see. Light is the fastest thing we know, traveling at 186,000 miles per second. The distances of objects are given in light-travel times—from 1.3 light-seconds for the Moon to 13.8 billion light-years for the CMB. For objects in the solar system, whose distances to us are constantly changing as we and they orbit the Sun, we indicate their distance at their closest point of approach to Earth. These distances, along with highlights of how each object was discovered and measured by astronomers, provide a framework and a narrative thread for the book, which is carried forward from one caption to the next. At each stage of this outward journey, you will learn new and surprising facts about fascinating objects we have found in the depths of space.

You will notice something a bit unusual about the images in this book. Not only will our visual tour of the universe move outward through the three-dimensional depths of space; the images themselves can be viewed in three dimensions, using a special viewer that you will find built into this book. Each pair of images, when viewed with the special stereo viewer (we will describe how to use it a little later on), portrays the celestial object or feature of the universe in three dimensions.

INTRODUCTION

Before we launch our journey through the depths of the cosmos, it is worthwhile to remind ourselves of the fact that it was only through careful observation and measurement of the gleaming and glimmering lights in the sky that human beings realized how distant these lights actually are. Let's explore in a little more detail the methods astronomers came up with to measure distances beyond Earth, stepping out from our own solar system to the furthest galaxies and outward toward the most distant light we can observe, the cosmic microwave background. As we introduce the different methods of measurement, we'll also find ourselves traveling in time, from the third century BC to the current frontiers of astronomy.

How to go about measuring the distances to even the nearest stars is far from obvious. We can't simply stretch a tape measure between here and a star. Humans had to think of another way of measuring distant objects, and we—that is, our insightful ancestors—came up with the concept of *parallax*. Parallax refers to the shifts that occur in the apparent positions of distant objects when your viewing location changes. It is also responsible for your 3D vision. Your two eyes produce slightly different pictures of objects in front of you, due to your eyes' slightly different locations; and these two different images, effortlessly interpreted by your brain, give you depth perception.

You can demonstrate the parallax effect for yourself with a quick experiment. Close your right eye and hold your thumb out at arm's length. Line your thumb up with an object in the distance using your left eye only. Now wink to the other eye. What happens? Your thumb appears to move. Now take your thumb and position it only half an arm's length from your eyes and repeat that exercise. Your thumb shifts even more. The larger the shift, the closer a foreground object is. That's how you judge distance.

Now, let's go back to the problem of how to measure the distance to a star. Obviously, if you use your own eyes to try to measure the distance to a star, you will not be successful. This is because the 2.5 inches between your eyeballs is not enough distance to give you significantly different perspectives on the faraway star. But people realized that they could use the parallax effect for observing stars if they could make observations from two locations sufficiently far apart and then compare them. The distance between one's eyes isn't much—but the diameter of Earth's orbit is 186 million miles. That's a nice wide distance for winking at the universe and deriving a measure of how close a star is.

Let's unpack this a bit further. Think of the nearby star as your thumb, and the diameter of Earth's orbit as the separation between your two eyes. As we know (though this was not immediately obvious to our distant ancestors), Earth orbits around the Sun (see figure 1—not to scale). Earth (the small blue dot) is on one side of the Sun in January and orbits to the other side six months later, in July. In the middle of the figure, there's a nearby star (shown in red), and then way out to the right is a field of much more distant stars.

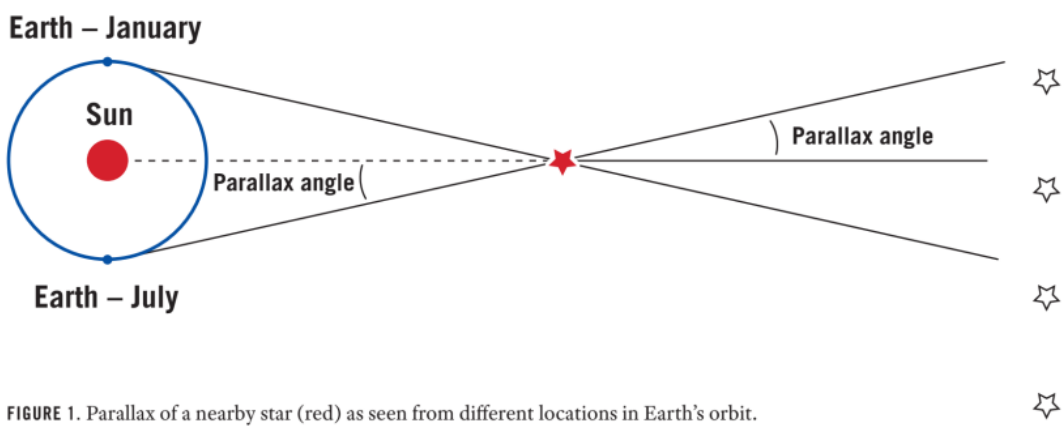

FIGURE 1. Parallax of a nearby star (red) as seen from different locations in Earth's orbit.

Imagine that, in January, we take a picture of the region around the nearby star (see the left of figure 2). We see many, many stars on that photograph, and one of them is the star in question (in red).

Alone, this picture tells us nothing, of course. Remember, we don't know yet which stars are close and which ones are far away. But, say we wait six months and take that picture again in July, from the opposite side of Earth's orbit. Earth has moved to a new position. We now see an identical starry background (as those other stars are much more distant)—but our (red) star appears to have moved from where it once was, to its new location as viewed from Earth in July. It has shifted, just like our thumbs shifted position when we winked our eyes, while everything else in the background basically stayed in the same place (see right side of figure 2).

FIGURE 2. Parallax shifts of a nearby star (red) seen between January and July.

What will happen in another six months? Our red star shifts back to where we saw it a year ago. That shifting just repeats itself, back and forth, over the course of a yearly cycle. Flash the two pictures back and forth, one after the other. If the two photographs are identical except for one star that moves, then we know that *that star* is the one that is closer than all the others. If this star were even closer (like when we moved our thumbs closer to our eyes), then its shift on the picture would be even bigger. Closer stars “shift” more. We put “shift” in quotes because the star is just sitting there—we are the ones moving back and forth around the Sun; the shift is really just due to the change of our perspective when we move from one side of the Sun to the other.

So, now that we understand the concept of parallax, how can it be used to actually measure distance? Note the parallax angle marked in figure 1 next to the nearby star (red). It denotes the angle by which our line of sight from Earth to the nearby star is tipped in the figure relative to horizontal in July. In January our line of sight from Earth to the star is tipped the same amount relative to horizontal in the opposite direction. So during the year, our line of sight oscillates back and forth by plus or minus the parallax angle about a horizontal line. Thus, the total parallax shift seen in figure 2 against the very distant stars (in white) is just two times that parallax angle (shown

Aristarchus in addition noticed that, if you look at the Moon at the moment of first quarter, when the Moon is exactly half-illuminated by the Sun as seen from Earth, the rays of the Sun are hitting the Moon from the side, perpendicular to one's line of sight to the Moon. Since the Sun and Moon appear separated by nearly 90° in the sky at this moment, the rays of the Sun hitting the Moon and the Earth at that time must be nearly parallel, and, therefore, the Sun must be much farther away than the Moon. This is illustrated in figure 3.

On the left of figure 3, we see how it would be if the Sun were only twice as far away as the Moon. Since the Moon is exactly half-illuminated by the Sun as seen from Earth, the angle between the Sun and Earth at the Moon must be a right angle (90°). If you were to measure the angle between the Sun and Moon in the sky at this instant, it would be 60° as indicated in the diagram. Euclidean geometry tells us that the sum of the three angles a triangle is 180°. So the parallax angle at the Sun is 30° (compare with figure 1). In other words, from the angle of 60° between the Sun and Moon in the sky you observed, you could figure out that if you stood on the Moon at that moment, your line of sight to the Sun would be tipped at 30° relative to the vertical in the diagram. You could then make a scale drawing of the triangle and determine that the Sun was two times as far away from Earth as the Moon.

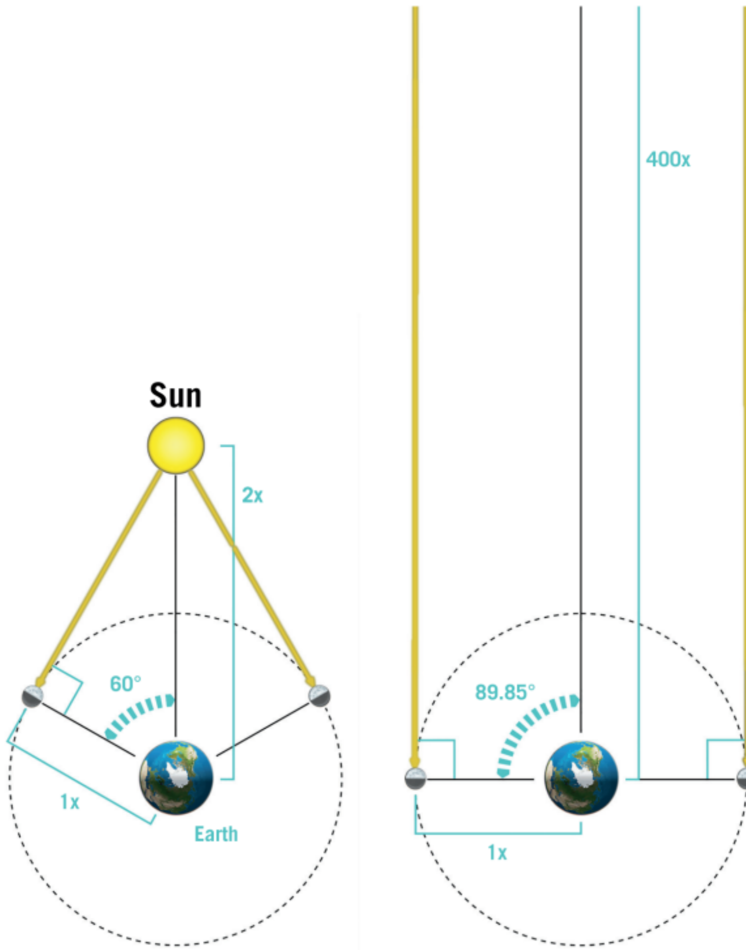

FIGURE 3. Aristarchus's method for measuring the distance to the Sun. On the left, the situation that would occur if the Sun were only twice as far away as the Moon. On the right, the actual situation where the Sun is about 400 times as far away as the Moon.

But that is not what Aristarchus saw. He saw that the Sun was nearly 90° away from the Moon in the sky when the Moon was at first quarter. That meant the Sun was very far away, as in the righthand side of figure 3. It was much farther away than the Moon. Compare figures 1 and 3. By his calculations, Aristarchus was effectively putting his eyes at the positions of the Moon at first and last quarter, to get a stereoscopic view of the Sun to determine its distance!

Let's use the actual values. At first quarter, the Moon is 89.85° away from the Sun in the sky. This means that the parallax angle at the Sun between the lines of sight from the Earth and the Moon is only 0.15°. It is a very tall, skinny triangle, and the Sun is far off the top of the page in the right-side diagram. Drawn to scale, the Sun is almost 400 times as far away as the Moon. Now Aristarchus's measurement was not quite as accurate as was required to learn that. He measured the angle between the Sun and Moon at first quarter to be 87°. Close to the real answer, but not quite. From his measurement he deduced that the parallax angle was 3° and that the Sun was 19 times farther away than the Moon. It still would be plotted off the top of the page in figure 3. He was quite correct in asserting that the Sun was much farther away than the Moon, but even then he underestimated its true distance.

Aristarchus then did some remarkable reasoning. Since the Sun and Moon had the same angular size, if the Sun were 19 times as far away as the Moon it must be 19 times the diameter of the Moon. And since he knew the Moon was about 1/3 the diameter of Earth, that meant that the Sun must be 19/3 or over 6 times the diameter of the Earth. The Sun was quite a bit bigger than Earth! Extrapolating from there, he figured that, if the smaller Moon orbits the larger Earth, then the smaller Earth should similarly orbit the even larger Sun. Though his distance estimate was an underestimate, his reasoning was good, and Aristarchus was correct in his conclusion that the Sun is bigger than the Earth (actually it is 109 times Earth's diameter). Through reasoning and measurement, he arrived at the heliocentric model of the solar system—17 centuries before Nicolas Copernicus adopted the same idea!

Sadly, people didn't believe Aristarchus. Unfortunately for Aristarchus (and scientific progress), Aristotle had previously argued that because we do not see the stars showing parallax shifts in a yearly cycle with the naked eye, Earth must be standing still, and does not circle the Sun. He concluded instead that the Earth is at the center of the universe, and that the Sun circles the Earth. Interestingly, Aristarchus had an answer for this. Aristarchus claimed that the stars were infinitely far away, and this was why the parallax was zero. That's not quite right, but he was on the right track! People believed Aristotle, not Aristarchus. It was one of the greatest misses in the history of science. Only in 1543, when Copernicus eventually came along with his book on the subject, were many scientists finally convinced that Earth orbits the Sun.

Why weren't parallax shifts detected in Aristotle's time? Stellar parallax shifts were not observed simply because the shifts are so very small. The naked eye can resolve angular sizes of only around one minute of arc (*arcminute*) or 1/60 of a degree. To get a feeling for how small this is, the Moon has an angular diameter in the sky of about 1/2 degree or 30 arcminutes. As we have noted, the actual parallax angles for even the nearest stars are all smaller than one *arcsecond* (that is, 1/3,600 of a degree)—completely undetectable with the naked eye. In 1543, Copernicus finally responded correctly to Aristotle's argument by saying that the parallax shifts of stars would be undetectable to the naked eye if the stars were simply at immense distances.

It was a long road to vindication for Aristarchus. And it took the invention of telescopes to enable us to actually observe stellar parallaxes. The first star outside our solar system to have its parallax angle measured was 61 Cygni (0.314 seconds of arc) by Friedrich Bessel in 1838. But this is the way science works. Over generations, over centuries, around the globe, astronomers have continually worked to make better observations

In 1922, American astronomer and Rhodes Scholar Edwin Hubble, working at Mount Wilson in California, found Cepheid variable stars in the Andromeda nebula far fainter than any Cepheid variables ever seen before. Using them as "standard candles," he found that this nebula was incredibly distant (the modern value is 2.5 million light-years away). His measurements proved that the Andromeda nebula lies far outside the confines of our Milky Way galaxy and is actually an entire galaxy like our own. In subsequent studies Hubble also discovered that the universe is filled with galaxies, and that the entire thing is expanding. You can think of galaxies in the expanding universe like raisins in a giant loaf of raisin bread, baking in an oven. As the dough expands, the raisins move away from each other. The farther they are apart, the faster they move away from each other. The same thing happens with galaxies. Velocities along our line of sight (which are called *radial velocities*) can be measured by the Doppler effect, the same effect that causes a train whistle to be higher in pitch as it approaches and lower in pitch as it goes away. Spectral lines in stars—particular stellar colors (wavelengths of light) missing from their spectrum because they are being absorbed by chemical elements the stars contain—are Doppler-shifted to the *blue* if the star is approaching us and shifted to the *red* if the star is receding. Hubble found that distant galaxies showed redshifts that were proportional to their distance.

Hubble thus observed that distant galaxies are receding, or moving away from us, and that galaxies twice as far away are moving away from us at twice the speed. This correlation between distance and recessional velocity soon became known as *Hubble's Law*.

By 1931, Hubble and his assistant Milton Humason had extended this relation between distance and recessional velocity to very distant galaxies moving away from us at speeds of up to 45 million miles per hour or 6.7% of the speed of light. This result finally convinced Albert Einstein that the universe is expanding, an idea that he had doubted up to that point. Now, imagine playing a movie of your baking loaf of raisin bread backward in time, and watching the dough contract, so that all the raisins come back toward each other until they all collide. One can imagine a similar time-reversed movie showing the universe contracting from its current state of expansion, so that everything in the universe can be tracked back to a single moment of beginning. This beginning was 13.8 billion years ago, in the form of a "Big Bang." Ever since, the universe has been expanding, with galaxies being flung to ever greater distances from each other. Today, we can use a distant galaxy's redshift (the measurement of how fast it is moving away from us) to estimate its distance to an accuracy of a few percent.

As our observational powers grew (via bigger telescopes, digital cameras, optical and radio telescopes in space), we continued to set our sights on measuring objects farther and farther away, to understand more about the structure and history of the universe. In 1997, two teams—including Adam Riess, Brian Schmidt, and Saul Perlmutter (who were awarded a Nobel Prize for their work in 2011)—found that the expansion of the universe is accelerating. The realization that the universe is expanding ever faster came as quite a surprise. The evidence that proved this came from using *supernovas* (exploding stars that could be calibrated as standard candles just as the Cepheid variables had been before them). But what was causing this startling behavior?

In 1917, Einstein still thought that the universe was static, neither expanding nor contracting. His field equations of general relativity didn't naturally predict a static universe, and to fix this apparent flaw Einstein added a term to his field equations he called the *cosmological constant*. Confronted with Hubble's overwhelming data showing an expanding universe in 1931, Einstein instantly dropped his cosmological constant idea. But in 1934 Belgian Catholic priest Georges Lemaître showed that, in an expanding universe, Einstein's cosmological constant term could still play a role and could be reinterpreted as something we now call *dark energy*. This fills empty space with a *positive energy density* and a *negative* pressure of equal magnitude. The pressure operates in three dimensions (up-down, left-right, front-back) and, being negative, produces a gravitationally repulsive effect. This repulsive effect, according to Einstein's equations, is therefore three times larger than the gravitationally attractive effect inherent to the energy density. This gives dark energy an overall gravitationally repulsive effect. Put another way, the total amount of matter and energy in the universe produces the universe's density—and, for the universe to be expanding at an accelerated rate, something must be counteracting the gravitational attraction of this matter and energy; the gravitationally repulsive negative pressure associated with dark energy nicely does the trick. In fact, by accurately measuring the expansion history of the universe and applying Einstein's original equations of general relativity we can determine the ratio of pressure to energy density in the dark energy; the Planck satellite team finds it to be: -1.008 ± 0.068, which agrees, within the observational errors, with the value of -1 predicted by Lemaître. Remarkable.

The amount of dark energy required to explain the observed acceleration is equivalent (according to Einstein's famous equation $E = mc^2$) to a mass-density of 6×10^{-30} grams per cubic centimeter. This is tiny, not noticeable on small scales—but on cosmic scales, the effects are dramatic. Dark energy is now causing the universe to start doubling in size every 12.2 billion years into the foreseeable future. With such doubling (1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1,024, etc.), the universe will grow very large indeed. By 122 billion years from now (after 10 doublings), the distances between galaxies should be 1,024 times as large as they are today.

Around 1980, physicist Alan Guth, and others, proposed the idea that the early universe went through an episode of *inflation*, in which an *extraordinarily large* amount of dark energy may have powered the Big Bang itself. In the beginning, there was a rapidly expanding sea of extremely high-energy dark energy, which caused the cosmos to double in size perhaps once every 3×10^{-38} seconds. Bubbles of lower energy would naturally form in this cosmic sea, like bubbles in a pot of boiling water. Each bubble could then turn into an entire universe and expand forever in the continually expanding, inflating sea. In this picture, our universe is just one of many bubble universes. Today we refer to this whole sea of bubble universes as the *multiverse*.

The bubble universe in which we live formed 13.8 billion years ago. Eventually the dark energy inside our expanding bubble decayed into normal particles (in perhaps as little as 10^{-35} seconds) creating a hot Big Bang. Greatly redshifted radiation (light) left over from this hot Big Bang can be seen today as the *cosmic microwave background*. This was discovered in 1965 by Arno Penzias and Robert Wilson working with a radio holes, along with comet tails, had appropriate parallaxes applied along their lengths. Three-dimensional scientific models and simulations by astronomers were used in some cases, and two appropriate movie frames from simulated flybys were chosen in other cases. Doppler redshift data were used to produce the depth in the pictures of the cosmic web and the Crab nebula.