CHAPTER 1

A COSMIC MYSTERY STORY: BEGINNINGS

The Initial Mystery that attends any journey is: how did the traveler reach his starting point in the first place?

—LOUISE BOGAN, *Journey Around My Room*

It was a dark and stormy night.

Early in 1916, Albert Einstein had just completed his greatest life's work, a decade-long, intense intellectual struggle to derive a new theory of gravity, which he called the general theory of relativity. This was not just a new theory of gravity, however; it was a new theory of space and time as well. And it was the first scientific theory that could explain not merely how objects move through the universe, but also how the universe itself might evolve.

There was just one hitch, however. When Einstein began to apply his theory to describing the universe as a whole, it became clear that the theory didn't describe the universe in which we apparently lived.

Now, almost one hundred years later, it is difficult to fully appreciate how much our picture of the universe has changed in the span of a single human lifetime. As far as the scientific community in 1917 was concerned, the universe was static and eternal, and consisted of a single galaxy, our Milky Way, surrounded by a vast, infinite, dark, and empty space. This is, after all, what you would guess by looking up at the night sky with your eyes, or with a small telescope, and at the time there was little reason to suspect otherwise.

In Einstein's theory, as in Newton's theory of gravity before it, gravity is a purely attractive force between all objects. This means that it is impossible to have a set of masses located in space at rest forever. Their mutual gravitational attraction will ultimately cause them to collapse inward, in manifest disagreement with an apparently static universe.

The fact that Einstein's general relativity didn't appear consistent with the then picture of the universe was a bigger blow to him than you might imagine, for reasons that allow me to dispense with a myth about Einstein and general relativity that has always bothered me. It is commonly assumed that Einstein worked in isolation in a closed room for years, using pure thought and reason, and came up with his beautiful theory, independent of reality (perhaps like some string theorists nowadays!). However, nothing could be further from the truth.

Einstein was always guided deeply by experiments and observations. While he performed many "thought experiments" in his mind and did toil for over a decade, he learned new mathematics and followed many false theoretical leads in the process before he ultimately produced a theory that was indeed mathematically beautiful. The single most important moment in establishing his love affair with general relativity, however, had to do with observation. During the final hectic weeks that he was completing his theory, competing with the German mathematician David Hilbert, he used his equations to calculate the prediction for what otherwise might seem an obscure astrophysical result: a slight precession in the "perihelion" (the point of closest approach) of Mercury's orbit around the Sun.

Astronomers had long noted that the orbit of Mercury departed slightly from that predicted by Newton. Instead of being a perfect ellipse that returned to itself, the orbit of Mercury precessed (which means that the planet does not return precisely to the same point after one orbit, but the orientation of the ellipse shifts slightly each orbit, ultimately tracing out a kind of spiral-like pattern) by an incredibly small amount: 43 arc seconds (about $^{1}/_{100}$ of a degree) per century.

When Einstein performed his calculation of the orbit using his theory of general relativity, the number came out just right. As described by an Einstein biographer, Abraham Pais: “This discovery was, I believe, by far the strongest emotional experience in Einstein’s scientific life, perhaps in all his life.” He claimed to have heart palpitations, as if “something had snapped” inside. A month later, when he described his theory to a friend as one of “incomparable beauty,” his pleasure over the mathematical form was indeed manifest, but no palpitations were reported.

The apparent disagreement between general relativity and observation regarding the possibility of a static universe did not last long, however. (Even though it did cause Einstein to introduce a modification to his theory that he later called his biggest blunder. But more about that later.) Everyone (with the exception of certain school boards in the United States) now knows that the universe is not static but is expanding and that the expansion began in an incredibly hot, dense Big Bang approximately 13.72 billion years ago. Equally important, we know that our galaxy is merely one of perhaps 400 billion galaxies in the observable universe. We are like the early terrestrial mapmakers, just beginning to fully map the universe on its largest scales. Little wonder that recent decades have witnessed revolutionary changes in our picture of the universe.

The discovery that the universe is not static, but rather expanding, has profound philosophical and religious significance, because it suggested that our universe had a beginning. A beginning implies creation, and creation stirs emotions. While it took several decades following the discovery in 1929 of our expanding universe for the notion of a Big Bang to achieve independent empirical confirmation, Pope Pius XII heralded it in 1951 as evidence for Genesis. As he put it:

> It would seem that present-day science, with one sweep back across the centuries, has succeeded in bearing witness to the august instant of the primordial Fiat Lux [Let there be Light], when along with matter, there burst forth from nothing a sea of light and radiation, and the elements split

> and churned and formed into millions of galaxies. Thus, with that concreteness which is characteristic of physical proofs, [science] has confirmed the contingency of the universe and also the well-founded deduction as to the epoch when the world came forth from the hands of the Creator. Hence, creation took place. We say: "Therefore, there is a Creator. Therefore, God exists!"

The full story is actually a little more interesting. In fact, the first person to propose a Big Bang was a Belgian priest and physicist named Georges Lemaître. Lemaître was a remarkable combination of proficiencies. He started his studies as an engineer, was a decorated artilleryman in World War I, and then switched to mathematics while studying for the priesthood in the early 1920s. He then moved on to cosmology, studying first with the famous British astrophysicist Sir Arthur Stanley Eddington before moving on to Harvard and eventually receiving a second doctorate, in physics from MIT.

In 1927, before receiving his second doctorate, Lemaître had actually solved Einstein's equations for general relativity and demonstrated that the theory predicts a nonstatic universe and in fact suggests that the universe we live in is expanding. The notion seemed so outrageous that Einstein himself colorfully objected with the statement "Your math is correct, but your physics is abominable."

Nevertheless, Lemaître powered onward, and in 1930 he further proposed that our expanding universe actually began as an infinitesimal point, which he called the "Primeval Atom" and that this beginning represented, in an allusion to Genesis perhaps, a "Day with No Yesterday."

Thus, the Big Bang, which Pope Pius so heralded, had first been proposed by a priest. One might have thought that Lemaître would have been thrilled with this papal validation, but he had already dispensed in his own mind with the notion that this scientific theory had theological consequences and had ultimately removed a paragraph in the draft of his 1931 paper on the Big Bang remarking on this issue.

Lemaître in fact later voiced his objection to the pope's 1951 claimed proof of Genesis via the Big Bang (not least because he realized that if his theory was later proved incorrect, then the Roman Catholic claims for Genesis might be contested). By this time, he had been elected to the Vatican's Pontifical Academy, later becoming its president. As he put it, "As far as I can see, such a theory remains entirely outside of any metaphysical or religious question." The pope never again brought up the topic in public.

There is a valuable lesson here. As Lemaître recognized, whether or not the Big Bang really happened is a scientific question, not a theological one. Moreover, even if the Big Bang had happened (which all evidence now overwhelmingly supports), one could choose to interpret it in different ways depending upon one's religious or metaphysical predilections. You can choose to view the Big Bang as suggestive of a creator if you feel the need or instead argue that the mathematics of general relativity explain the evolution of the universe right back to its beginning without the intervention of any deity. But such a metaphysical speculation is independent of the physical validity of the Big Bang itself and is irrelevant to our understanding of it. Of course, as we go beyond the mere existence of an expanding universe to understand the physical principles that may address its origin, science can shed further light on this speculation and, as I shall argue, it does.

In any case, neither Lemaître nor Pope Pius convinced the scientific world that the universe was expanding. Rather, as in all good science, the evidence came from careful observations, in this case done by Edwin Hubble, who continues to give me great faith in humanity, because he started out as a lawyer and then became an astronomer.

Hubble had earlier made a significant breakthrough in 1925 with the new Mount Wilson 100-inch Hooker telescope, then the world's largest. (For comparison, we are now building telescopes more than ten times bigger than this in diameter and one hundred times bigger in area!) Up until that time, with the telescopes then available, astronomers were able to discern fuzzy images of objects that were not simple stars in our galaxy. They called these nebulae, which is basically Latin for "fuzzy thing" (actually "cloud"). They also debated whether these objects were in our galaxy or outside of it.

Since the prevailing view of the universe at the time was that our galaxy was all that there was, most astronomers fell in the "in our galaxy" camp, led by the famous astronomer Harlow Shapley at Harvard. Shapley had dropped out of school in fifth grade and studied on his own, eventually going to Princeton. He decided to study astronomy by picking the first subject he found in the syllabus to study. In seminal work he demonstrated that the Milky Way was much larger than previously thought and that the Sun was not at its center but simply in a remote, uninteresting corner. He was a formidable force in astronomy and therefore his views on the nature of nebulae held considerable sway.

On New Year's Day 1925, Hubble published the results of his two-year study of so-called spiral nebulae, where he was able to identify a certain type of variable star, called a Cepheid variable star, in these nebulae, including the nebula now known as Andromeda.

First observed in 1784, Cepheid variable stars are stars whose brightness varies over some regular period. In 1908, an unheralded and at the time unappreciated would-be astronomer, Henrietta Swan Leavitt, was employed as a "computer" at the Harvard College Observatory. ("Computers" were women brought in to catalogue the brightness of stars recorded on the observatory's photographic plates; women were not allowed to use the observatory telescopes at the time.) Daughter of a Congregational minister and a descendant of the Pilgrims, Leavitt made an astounding discovery, which she further illuminated in 1912: she noticed that there was a regular relationship between the brightness of Cepheid stars and the period of their variation. Therefore, if one could determine the distance to a single Cepheid of a known period (subsequently determined in 1913), then measuring the brightness of other Cepheids of the same period would allow one to determine the distance to these other stars!

Since the observed brightness of stars goes down inversely with the square of the distance to the star (the light spreads out uniformly over a sphere whose area increases as the square of the distance, and thus since the light is spread out over a bigger sphere, the intensity of the light observed at any point decreases inversely with the area of the sphere), determining the distance to faraway stars has always been the major challenge in astronomy. Leavitt's discovery revolutionized the field. (Hubble himself, who was snubbed for the Nobel Prize, often said Leavitt's work deserved the prize, although he was sufficiently self-serving that he might have suggested it only because he would have been a natural contender to share the prize with her for his later work.) Paperwork had actually begun in the Royal Swedish Academy to nominate Leavitt for the Nobel in 1924 when it was learned that she had died of cancer three years earlier. By dint of his force of personality, knack for self-promotion, and skill as an observer, Hubble would become a household name, while Leavitt, alas, is known only to aficionados of the field.

Hubble was able to use his measurement of Cepheids and Leavitt's period-luminosity relation to prove definitively that the Cepheids in Andromeda and several other nebulae were much too distant to be inside the Milky Way. Andromeda was discovered to be another island universe, another spiral galaxy almost identical to our own, and one of the more than 100 billion other galaxies that, we now know, exist in our observable universe. Hubble's result was sufficiently unambiguous that the astronomical community—including Shapley, who, incidentally, by this time had become director of the Harvard College Observatory, where Leavitt had done her groundbreaking work—quickly accepted the fact that the Milky Way is not all there is around us. Suddenly the size of the known universe had expanded in a single leap by a greater amount than it had in centuries! Its character had changed, too, as had almost everything else.

After this dramatic discovery, Hubble could have rested on his laurels, but he was after bigger fish or, in this case, bigger galaxies. By measuring ever fainter Cepheids in ever more distant galaxies, he was able to map the universe out to ever-larger scales. When he did, however, he discovered something else that was even more remarkable: the universe is expanding!

Hubble achieved his result by comparing the distances for the galaxies he measured with a different set of measurements from another American astronomer, Vesto Slipher, who had measured the spectra of light coming from these galaxies. Understanding the existence and nature of such spectra requires me to take you back to the very beginning of modern astronomy.

One of the most important discoveries in astronomy was that star stuff and Earth stuff are largely the same. It all began, as did many things in modern science, with Isaac Newton. In 1665, Newton, then a young scientist, allowed a thin beam of sunlight, obtained by darkening his room except for a small hole he made in his window shutter, through a prism and saw the sunlight disperse into the familiar colors of the rainbow. He reasoned that white light from the sun contained all of these colors, and he was correct.

A hundred fifty years later, another scientist examined the dispersed light more carefully, discovered dark bands amidst the colors, and reasoned that these were due to the existence of materials in the outer atmosphere of the sun that were absorbing light of certain specific colors or wavelengths. These "absorption lines," as they became known, could be identified with wavelengths of light that were measured to be absorbed by known materials on Earth, including hydrogen, oxygen, iron, sodium, and calcium.

In 1868, another scientist observed two new absorption lines in the yellow part of the solar spectrum that didn't correspond to any known element on Earth. He decided this must be due to some new element, which he called helium. A generation later, helium was discovered on Earth.

Looking at the spectrum of radiation coming from other stars is an important scientific tool for understanding their composition, temperature, and evolution. Starting in 1912, Slipher observed the spectra of light coming from various spiral nebulae and found that the spectra were similar to those of nearby stars—except that all of the absorption lines were shifted by the same amount in wavelength.

This phenomenon was by then understood as being due to the familiar "Doppler effect," named after the Austrian physicist Christian Doppler, who explained in 1842 that waves coming at you from a moving source will be stretched if the source is moving away from you and compressed if it is moving toward you. This is a manifestation of a phenomenon we are all familiar with, and by which I am usually reminded of a Sidney Harris cartoon where two cowboys sitting on their horses out in the plains are looking at a distant train, and one says to the other, “I love hearing that lonesome wail of the train whistle as the magnitude of the frequency changes due to the Doppler effect!” Indeed, a train whistle or an ambulance siren sounds higher if the train or ambulance is moving toward you and lower if it is moving away from you.

It turns out that the same phenomenon occurs for light waves as sound waves, although for somewhat different reasons. Light waves from a source moving away from you, either due to its local motion in space or due to the intervening expansion of space, will be stretched, and therefore appear redder than they would otherwise be, since red is the long-wavelength end of the visible spectrum, while waves from a source moving toward you will be compressed and appear bluer.

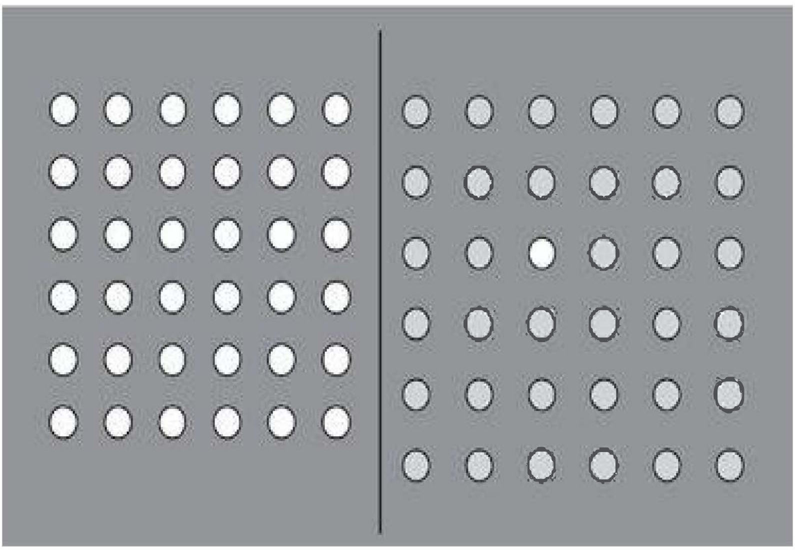
Slipher observed in 1912 that the absorption lines from the light coming from all the spiral nebulae were almost all shifted systematically toward longer wavelengths (although some, like Andromeda, were shifted toward shorter wavelengths). He correctly inferred that most of these objects therefore were moving away from us with considerable velocities.

Hubble was able to compare his observations of the distance of these spiral galaxies (as they were by now known to be) with Slipher’s measurements of the velocities by which they were moving away. In 1929, with the help of a Mount Wilson staff member, Milton Humason (whose technical talent was such that he had secured a job at Mount Wilson without even having a high school diploma), he announced the discovery of a remarkable empirical relationship, now called Hubble’s law: There is a linear relationship between recessional velocity and galaxy distance. Namely, galaxies that are ever more distant are moving away from us with faster velocities!

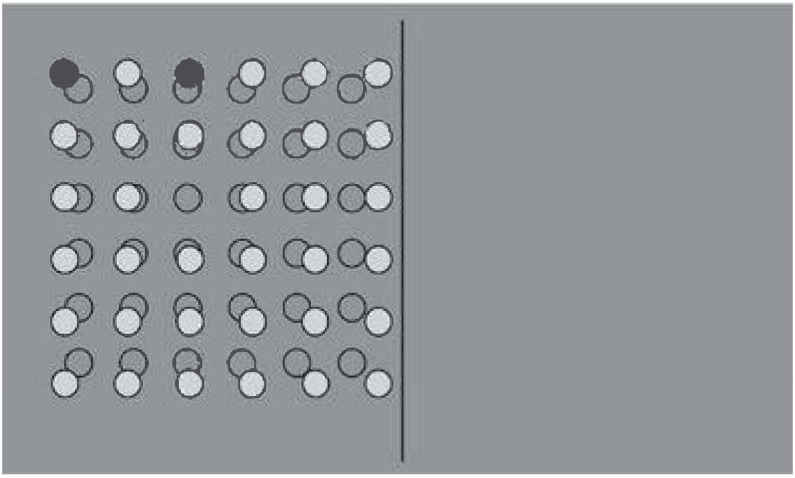
When first presented with this remarkable fact—that almost all galaxies are moving away from us, and those that are twice as far away are moving twice as fast, those that are three times away three times as fast, etc.—it seems obvious what this implies: *We are the center of the universe!*

As some friends suggest, I need to be reminded on a daily basis that *this is not the case*. Rather, it was consistent with precisely the relationship that Lemaître had predicted. Our universe is indeed expanding.

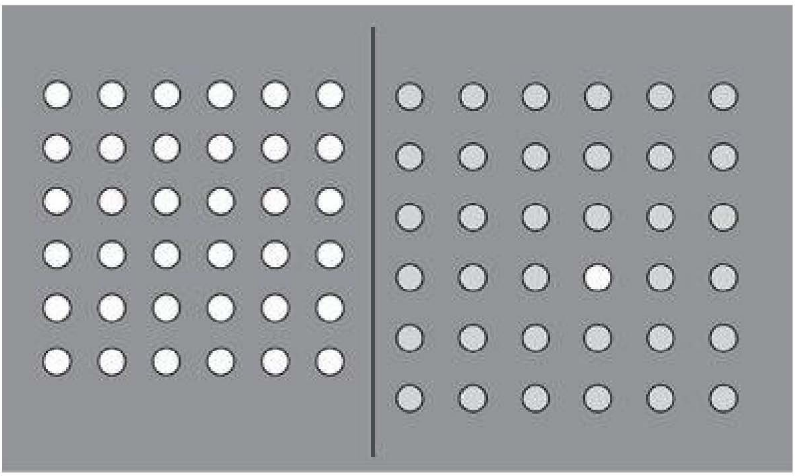
I have tried various ways to explain this, and I frankly don't think there is a good way to do it unless you think outside the box—in this case, outside the universal box. To see what Hubble's law implies, you need to remove yourself from the myopic vantage point of our galaxy and look at our universe from the outside. While it is hard to stand outside a three-dimensional universe, it is easy to stand outside a two-dimensional one. On the next page I have drawn one such expanding universe at two different times. As you can see, the galaxies are farther apart at the second time.



Now imagine that you are living in one of the galaxies at the second time, t_2 which I shall mark in white, at time t_2.

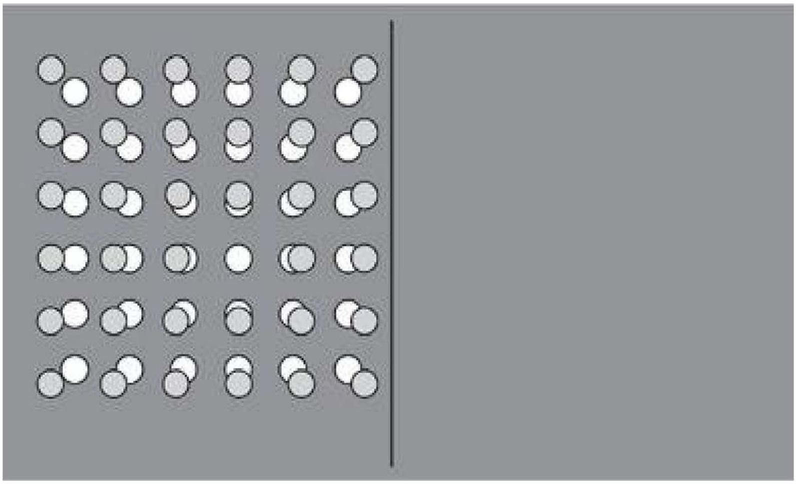


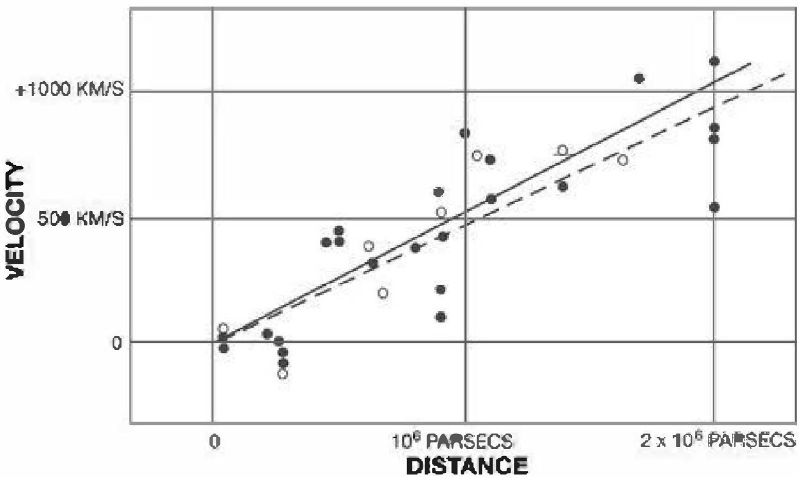
To see what the evolution of the universe would look like from this galaxy's vantage point, I simply superimpose the right image on the left, placing the galaxy in white on top of itself.



Voilà! From this galaxy's vantage point every other galaxy is moving away, and those that are twice as far have moved twice the distance in the same time, those that are three times as far away have moved three times the distance, etc. As long as there is no edge, those on the galaxy feel as if they are at the center of the expansion.

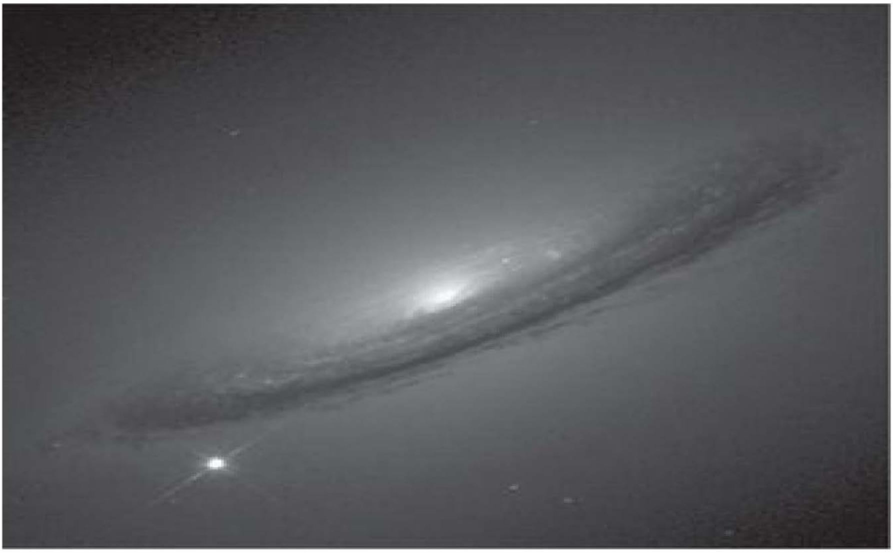
It doesn't matter what galaxy one chooses. Pick another galaxy, and repeat:





Depending upon your perspective, then, either *every place* is the center of the universe, or *no place* is. It doesn't matter; Hubble's law is consistent with a universe that is expanding.

Now, when Hubble and Humason first reported their analysis in 1929, they not only reported a linear relationship between distance and recession velocity, but also gave a quantitative estimate of the expansion rate itself. Here are the actual data presented at the time:



As you can see, Hubble's guess of fitting a straight line to this data set seems a relatively lucky one. (There is clearly some relationship, but whether a straight line is the best fit is far from clear on the basis of this data alone.) The number for the expansion rate they obtained, derived for the plot, suggested that a galaxy a million parsecs away (3 million light-years)—the average separation between galaxies—is moving away from us with a speed of 500 kilometers/second. This estimate was not so lucky, however.

The reason for this is relatively simple to see. If everything is moving apart today, then at earlier times they were closer together. Now, if gravity is an attractive force, then it should be slowing the expansion of the universe. This means the galaxy we see moving away from us at 500 kilometers/second today would have been moving faster earlier.

If for the moment, though, we just assume that the galaxy had always been carried away with that velocity, we can work backward and figure out how long ago it would have been at the same position as our galaxy. Since galaxies twice as far away are moving twice as fast, if we work backward we find out that they were superimposed on our position at exactly the same time. Indeed, the entire observable universe would have been superimposed at a single point, the Big Bang, at a time that we can estimate in this way.

Such an estimate is clearly an upper limit on the age of the universe, because, if the galaxies were once moving faster, they would have gotten where they are today in less time than this estimate would suggest.

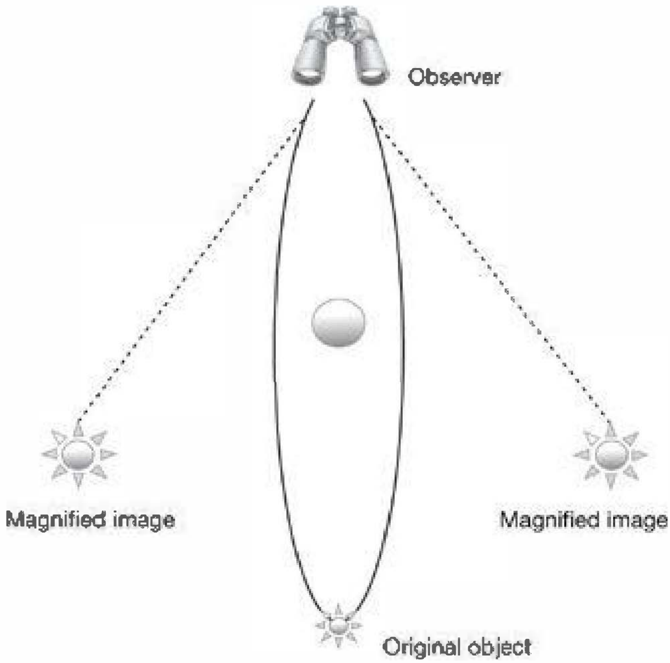
From this estimate based on Hubble's analysis, the Big Bang happened approximately 1.5 billion years ago. Even in 1929, however, the evidence was already clear (except to some scriptural literalists in Tennessee, Ohio, and a few other states) that the Earth was older than 3 billion years old.

Now, it is embarrassing for scientists to find that the Earth is older than the universe. More important, it suggests something is wrong with the analysis.

The source of this confusion was simply the fact that Hubble's distance estimates, derived using the Cepheid relations in our galaxy, were systematically incorrect. The distance ladder based on using nearby Cepheids to estimate the distance of farther away Cepheids, and then to estimate the distance to galaxies in which yet more distant Cepheids were observed, was flawed.

The history of how these systematic effects have been overcome is too long and convoluted to describe here and, in any case, no longer matters because we now have a much better distance estimator.

One of my favorite Hubble Space Telescope photographs is shown below:



It shows a beautiful spiral galaxy far far away, long long ago (long long ago because the light from the galaxy takes some time —more than 50 million years—to reach us). A spiral galaxy such as this, which resembles our own, has about 100 billion stars within it. The bright core at its center contains perhaps 10 billion stars. Notice the star on the lower left corner that is shining with a brightness almost equal to these 10 billion stars. On first sighting it, you might reasonably assume that this is a much closer star in our own galaxy that got in the way of the picture. But in fact, it is a star in that same distant galaxy, more than 50 million light-years away.

Clearly, this is no ordinary star. It is a star that has just exploded, a supernova, one of the brightest fireworks displays in the universe. When a star explodes, it briefly (over the course of about a month or so) shines in visible light with a brightness of 10 billion stars.

Happily for us, stars don't explode that often, about once per hundred years per galaxy. But we are lucky that they do, because if they didn't, we wouldn't be here. One of the most poetic facts I know about the universe is that essentially every atom in your body was once inside a star that exploded. Moreover, the atoms in your left hand probably came from a different star than did those in your right. We are all, literally, star children, and our bodies made of stardust.

How do we know this? Well, we can extrapolate our picture of the Big Bang back to a time when the universe was about 1 second old, and we calculate that all observed matter was compressed in a dense plasma whose temperature should have been about 10 billion degrees (Kelvin scale). At this temperature nuclear reactions can readily take place between protons and neutrons as they bind together and then break apart from further collisions. Following this process as the universe cools, we can predict how frequently these primeval nuclear constituents will bind to form the nuclei of atoms heavier than hydrogen (i.e., helium, lithium, and so on).

When we do so, we find that essentially no nuclei—beyond lithium, the third lightest nucleus in nature—formed during the primeval fireball that was the Big Bang. We are confident that our calculations are correct because our predictions for the cosmic abundances of the lightest elements agree bang-on with these observations. The abundances of these lightest elements—hydrogen, deuterium (the nucleus of heavy hydrogen), helium, and lithium—vary by 10 orders of magnitude (roughly 25 percent of the protons and neutrons, by mass, end up in helium, while 1 in every 10 billion neutrons and protons ends up within a lithium nucleus). Over this incredible range, observations and theoretical predictions agree.

This is one of the most famous, significant, and successful predictions telling us the Big Bang really happened. *Only a hot Big Bang can produce the observed abundance of light elements and maintain consistency with the current observed expansion of the universe.* I carry a wallet card in my back pocket showing the comparison of the predictions of the abundance of light elements and the observed abundance so that, each time I meet someone who doesn't believe that the Big Bang happened, I can show it to them. I usually never get that far in my discussion, of course, because data rarely impress people who have decided in advance that something is wrong with the picture. I carry the card anyway and reproduce it for you later in the book.

While lithium is important for some people, far more important to the rest of us are all the heavier nuclei like carbon, nitrogen, oxygen, iron, and so on. These were *not* made in the Big Bang. The only place they can be made is in the fiery cores of stars. And the only way they could get into your body today is if these stars were kind enough to have exploded, spewing their products into the cosmos so they could one day coalesce in and around a small blue planet located near the star we call the Sun. Over the course of the history of our galaxy, about 200 million stars have exploded. These myriad stars sacrificed themselves, if you wish, so that one day you could be born. I suppose that qualifies them as much as anything else for the role of saviors.

It turns out a certain type of exploding star, called a Type Ia supernova, has been shown by careful studies performed over the 1990s to have a remarkable property: with high accuracy, those Type Ia supernovae that are intrinsically brighter also shine longer. The correlation, while not fully understood theoretically, is empirically very tight. This means that these supernovae are very good "standard candles." By this we mean that these supernovae can be used to calibrate distances because their intrinsic brightness can be directly ascertained by a measurement that is independent of their distance. If we observe a supernova in a distant galaxy—and we can because they are very bright—then by observing how long it shines, we can infer its intrinsic brightness. Then, by measuring its apparent brightness with our telescopes, we can accurately infer just how far away the supernova and its host galaxy are. Then, by measuring the "redshift" of the light from the stars in the galaxy, we can determine its velocity, and thus can compare velocity with distance and infer the expansion rate of the universe.

So far so good, but if supernovae explode only once every hundred years or so per galaxy, how likely are we ever to be able to see one? After all, the last supernova in our own galaxy witnessed on Earth was seen by Johannes Kepler in 1604! Indeed, it is said that supernovae in our galaxy are observed only during the lifetimes of the greatest astronomers, and Kepler certainly fits the bill.

Starting out as a humble mathematics teacher in Austria, Kepler became assistant to the astronomer Tycho Brahe (who himself had observed an earlier supernova in our galaxy and was given an entire island by the king of Denmark in return), and using Brahe's data on planetary positions in the sky taken over more than a decade, Kepler derived his famous three laws of planetary motion early in the seventeenth century:

1. Planets move around the Sun in ellipses.
2. A *line* connecting a planet and the Sun sweeps out equal *areas* during equal intervals of time.
3. The *square* of the *orbital period* of a planet is directly *proportional* to the *cube* (3rd power) of the *semi-major axis* of its orbit (or, in other words, of the "semi-major axis" of the ellipse, half of the distance across the widest part of the ellipse).

These laws in turn lay the basis for Newton's derivation of the universal law of gravity almost a century later. Besides this remarkable contribution, Kepler successfully defended his mother in a witchcraft trial and wrote what was perhaps the first science fiction story, about a journey to the moon.

Nowadays, one way to see a supernova is simply to assign a different graduate student to each galaxy in the sky. After all, one hundred years is not too different, in a cosmic sense at least, from the average time to do a PhD, and graduate students are cheap and abundant. Happily, however, we don't have to resort to such extreme measures, for a very simple reason: the universe is big and old and, as a result, rare events happen all the time.

Go out some night into the woods or desert where you can see stars and hold up your hand to the sky, making a tiny circle between your thumb and forefinger about the size of a dime. Hold it up to a dark patch of the sky where there are no visible stars. In that dark patch, with a large enough telescope of the type we now have in service today, you could discern perhaps 100,000 galaxies, each containing billions of stars. Since supernovae explode once per hundred years per, with 100,000 galaxies in view, you should expect to see, on average, about three stars explode on a given night.

Astronomers do just this. They apply for telescope time, and some nights they might see one star explode, some nights two, and some nights it might be cloudy and they might not see any. In this way several groups have been able to determine Hubble's constant with an uncertainty of less than 10 percent. The new number, about 70 kilometers per second for galaxies on average of 3 million light-years apart, is almost a factor of 10 smaller than that derived by Hubble and Humason. As a result, we infer an age of the universe of closer to 13 billion years, rather than 1.5 billion years.

As I shall describe later, this too is in complete agreement with independent estimates of the age of the oldest stars in our galaxy. From Brahe to Kepler, from Lemaître to Einstein and Hubble, and from the spectra of stars to the abundance of light elements, four hundred years of modern science have produced a remarkable and consistent picture of the expanding universe. Everything holds together. The Big Bang picture is in good shape.