



the big picture

At first, the idea of understanding the universe seems preposterous, presumptuous, or in any case, out of reach, precisely because the universe is not built on a human scale of time or size. But we now have a physical picture of the history and evolution of the universe. How have we overcome the limitations of our small brains, our short lives, and our absurdly small stature to understand an ancient and immense universe?

We're so *brief*. The stars seem permanent, but that's only because we're just passing through. If you live for 100 years that's only one part in 100 million of the age of the universe. How can you expect to see the flow of cosmic change? Comparing your lifetime to the age of the universe is like comparing the longest time you can hold your breath to your lifetime. That's it. One breath is to one lifetime as one lifetime is to the age of universe. Inhale deeply!

Cosmic time numbs our sense of history. All of recorded human history reaches back only 10,000 years: 100 generations for 100 years each. Deep cosmic time stretches back a *million* times farther than the first glimmer of civilization when dogs decided to join humans in their caves. With a few spectacular exceptions, as when stars destroy themselves in supernova explosions, we have no chance to see the universe change during one lifetime, even though we know processes of change must be at work. But by learning

what supernovae are, how they work, and how to use them, we can trace the history of cosmic expansion deep into the distant past.

And we're *short*. So short that we can't see the curve of the spherical Earth, which is 10 million times bigger than a person. Our common sense view of a flat Earth is wrong because the Earth, to say nothing of larger astronomical objects, is not built to our scale.¹ We usually learn our planet's shape by meekly accepting dogma from third-grade teachers teaching the Columbus Day curriculum. A better way is to launch people off Earth's surface to take a look. Astronauts travel for us and bring back pictures that illuminate the true spherical geometry of the Earth. Even though we knew what these pictures would show, images of a round planet conquer our common sense and move a spherical Earth into our intuition.

Stepping back to get perspective doesn't work so well for learning the shape of larger astronomical objects. Just as a slice of pepperoni sizzling amid the mozzarella has a hard time seeing the whole pizza, we have a hard time seeing the flattened disk of the galaxy in which the sun is located. We have no perspective on the shape of our Milky Way galaxy and there's no stepping back. Our difficulty in imagining the shape of the universe in which the Milky Way and 100 billion equivalent systems reside is even more acute: there is no way to get outside for some perspective.

How do we overcome these limitations to gain a picture of the universe? Although we have small brains, brief lives, and a common sense that seems certain to lead us astray, the case is not altogether desperate. The problem isn't the size of our brains, it's having the right ideas. Over the past 500 years we have begun to puzzle out where we are and how things work.

Human imagination can begin to explore the possibilities. The old German 10-mark note, now displaced by the Euro, depicted Karl Friedrich Gauss, prince of mathematicians. His civil service job was to direct the astronomical observatory at Göttingen. Astronomers invoke his name daily, using his bell-shaped curve to evaluate the effects of chance on every type of astronomical evidence from motions in the solar system all the way out to tracing the bubbling variations in the glow from the hot Big Bang.²



Figure 1.1. The 4-meter Victor and Betty Blanco telescope at Cerro Tololo in Chile, silhouetted against the Milky Way Galaxy. In 1917, when Einstein first considered the effects of gravity on the universe as a whole, astronomers thought that the Milky Way was the entire universe. Today we think of it as one galaxy among 100 billion similar systems. The Large and Small Magellanic Clouds are to the left. Courtesy of Roger Smith/NOAO/AURA/NSF

Ideas of curved space were worked out by Gauss in the 1820s and advanced in the 1850s by his brilliant student and colleague at Göttingen, Bernhard Riemann. Being a mathematician, Riemann was not constricted to thinking about two-dimensional spaces like the surface of a beach ball, but thought through general properties of curvature for mathematical spaces with three or four or many more dimensions.

In 1915, Albert Einstein needed those ideas of curved space to construct a new theory of gravity. In Einstein's general relativity, the presence of matter and energy warps a four-dimensional space-time and affects the way light travels through the universe. Mathematics developed by mathematicians for their own reasons turned



Figure 1.2. Karl Friedrich Gauss on the 10-mark note. Gauss had early success in predicting orbits and became director of the observatory at Göttingen. The bell-shaped curve of probability looming over Gauss's shoulder describes the likelihood of obtaining, by chance, an experimental result that differs from the true value. When astronomers quote the age of the universe with a band of uncertainty, or the odds that the data imply a cosmological constant, they use the ideas of Gauss.

out to be just the tool that Einstein needed to describe the physical world. Gravity is weak here and the solar system is very small, so curved space makes only subtle differences in the solar system, just as the curvature of the Earth makes only subtle differences in laying out a baseball diamond. But over cosmic distances the curvature of space matters. Einstein's general theory of relativity describes the way matter and energy curve the universe and how the contents of the universe make it expand or contract on the biggest imaginable scale. Using exploding stars, the heat left over from the Big Bang, and a strong web of physical understanding developed over centuries, we now have our first real glimpse of cosmic history and cosmic geometry.

No person has to construct our picture of the universe single-handedly: science lets us accumulate the understanding of very fine brains of the past such as those of Gauss and Einstein, cooperate and compete with other people today, and harness rapidly improving technology to sift vast haystacks of data. Other aspects of culture may or may not have improved from the time of Shakespeare or Mozart or Rembrandt, but science today is most definitely better than the science of past centuries, or even the past decade. We get to use every good idea and measurement from the past because

scientists publish their findings in carefully screened journals. We get to use sharp new tools like the Hubble Space Telescope (HST), giant electronic cameras, and powerful computers for present-day exploration. In this way, more-or-less ordinary people today can make far better measurements than Galileo or Newton or Hubble ever could. Since we get to peek at Einstein's homework and have new and powerful tools of observation, we would be dull astronomers indeed if we couldn't make some progress in learning the history of the universe.

We can decode the universe because the laws of physics discovered on Earth also work in distant places. Gravity accelerating a roller coaster (and its thrilled riders) on the Boardwalk at Santa Cruz is just the local form of universal gravitation that keeps planets and asteroids in their orbits, steers stars around in clusters and galaxies, and determines whether the universe will expand forever. Atoms of calcium, whether in your femur, the sun's atmosphere, or in the atmospheres of stars in a distant galaxy, are interchangeable units governed by electrical forces that interact through precisely the same quantum mechanical laws here and there. The way an atom emits or absorbs light in a fluorescent tube in the humming control room of a telescope is identical to the way a similar atom behaves in an exploding star. You can tell which chemical elements are in a star and how that star is moving by gathering its light with a telescope, then delicately dissecting it into a spectrum. Less familiar laws of physics, discovered in particle accelerators on Earth, govern the weak and strong forces that tell how subatomic particles are assembled and how they push and pull on each other. These laws of physics, combined with human imagination and guided by astronomical observations, tell us how the stars shine and what makes some of them explode as supernovae, and let us interpret the clues to the past that a hot, expanding universe leaves behind as evidence.

Despite these successes, human imagination is a weak thing. The universe is wilder than we imagine: we keep underestimating how weird it really is. So astronomy is not exactly an experimental science in which the thoughtful predictions of physical theory get tested. Astronomy is a science driven by discovery, since the objects

we observe are stranger and more exotic than even the most unbridled speculators predict. Where the physical effects are simple, astronomy resembles physics. For example, glowing embers of a vanished hot Big Bang can be detected in every direction as a faint radio hiss we call the cosmic microwave background. Predictions and measurements of this background radiation provide sharp tests for the simple physics of a hot Big Bang. But, where the phenomena have many too many moving parts for a simple analysis, astronomical observations lead the way. Once the universe got complex, as matter formed into stars, it grew less predictable and far more interesting. The exact mechanisms by which stars explode in thermonuclear blasts are still not fully understood and were not predicted by even the most uninhibited minds. Yet we see exploding stars that shine with the light of a billion suns. Just because we can't yet compute exactly how a thermonuclear flame destroys a star doesn't mean we can't measure the behavior of supernovae well enough to make them into yardsticks for measuring the size of the universe. Astronomers are used to building a case from fragmentary evidence, circumstantial evidence, and hearsay. Often there's no way to perform a controlled experiment on Earth to test astronomical theories, but we can assemble enough lines of evidence from observations to see if we're on the right path.

Most astronomy applies known laws of physics to astronomical settings, but some astronomical measurements reveal fundamental properties of the world: the underlying rules of behavior for matter and energy. Astronomical objects create settings we cannot reproduce in terrestrial laboratories.

One fundamental physical property of the world that was discovered by astronomical observation is the finite speed of light. In 1676, the Dane Ole Rømer was working in Paris, observing the moons of Jupiter. The eclipses of those moons as they ducked behind Jupiter could be predicted, but the measurements had pesky seasonal errors. Rømer had a good clock on the steady floor of the Observatoire de Paris. He noticed that in the months when the Earth's orbit around the sun brought us closer to Jupiter, the eclipses were a little early, and at other times of the year when the Earth

was farther from Jupiter, the eclipses were late. Rømer inferred that light takes time to cross the diameter of the Earth's orbit. He measured this time delay to be about 16 minutes. In Rømer's time this fundamental measurement of a profoundly important physical effect—the finite speed of light—could only be done by astronomical observations. Light travels a foot in a nanosecond, a billionth of a second.³ In the age of pendulum clocks, there was no laboratory apparatus capable of measuring such short time intervals over indoor distances. The speed of light wasn't measured on Earth until 1850, when Fizeau set up an ingenious optical device with a rapidly spinning mirror in the very same observatory. More recently, the energy and pressure associated with empty space itself is not (at least in the year 2002) detected by any laboratory experiment and is not the natural outcome of any well-established physical theory. This fundamental property shows itself only in astronomical measurements of distant supernovae that reveal an accelerating universe, which is part of the reason why this work has been so exciting.

The sluggishness of light gives astronomy, like geology, the historical reach to examine the past. We never see things as they are. We always see things the way they were when light left them. For objects in a room, that was a few nanoseconds ago. Based on terrestrial experiences, we can be excused for thinking we see things as they are. But on the astronomical scale, the effects of time ticking by while light travels are very important. They allow us to overcome our own brief lives to see how the universe has changed over long stretches of cosmic time. Light travel time transforms a telescope into a no-hokum time machine.⁴ Instead of seeing a frozen moment, “now,” throughout space, we see a slice through time and space: we see the present nearby, and the past when we look far away. We can trace the history of the universe by direct observation of the past, limited only by the power of our instruments.

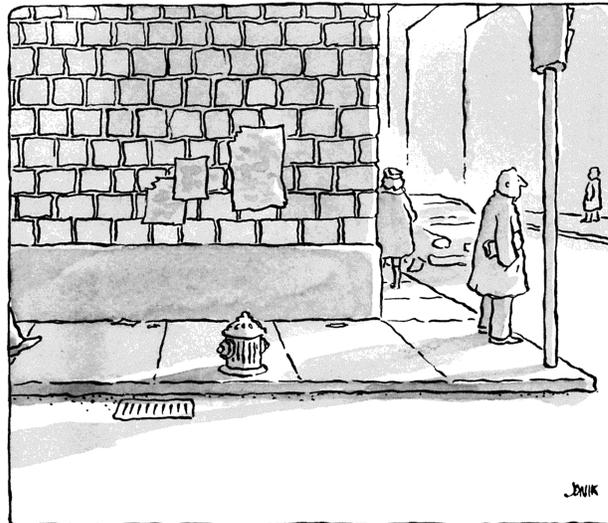
So far, we have no way to see the future, but we can use direct measurements of the past and our physical understanding of how things work to predict the future. The stars do not predict our future, but we can predict the future of the stars, based on a firm grip of

events on the scale of atomic nuclei that keep stars shining. For stars, these predictions can be tested, because we see stars of various ages, and we can trace their life cycles from birth through maturity to a death that can be quiet or violent.

The finite speed of light is woven into the language of astronomy—we use the term “light-year” to mean the distance that light travels in a year.⁵ The time it takes for light to reach us from a star 100 light-years away is just a century. You can walk out tonight and see stars whose light was emitted before your parents were born. Light from the most distant supernova so far observed carries information about the way the universe has been expanding over the past 10 billion years, two-thirds of the way back to the origin of time at the Big Bang. Measuring the light from these very distant stars is not easy—the sky is bright, the stars are dim, and there are many pitfalls for the unwary—but the rewards for assembling a coherent picture of the universe are great.

In 1917, when Einstein began to connect his newly minted gravity-as-geometry with the universe, astronomers thought the stars of the Milky Way were the entire contents of the universe. Now we know the Milky Way galaxy is not the whole universe but just a small part of it. Stars form in colossal galaxies and the galaxies, each one 100 billion stars like the sun, are the units we can see that trace the underlying properties of the universe.

The sun is located in one of the outer spiral arms of the Milky Way, about 20,000 light-years from the center. All the stars you can see at night are in the Milky Way galaxy, and many of them are in that faint flattened band of light that city dwellers never see. The generous size of the galaxy means that many momentous events have already taken place, but we just carry on in ignorance because the news hasn't yet reached us. Andrew Jackson, Old Hickory, won the Battle of New Orleans in 1815, 15 days *after* the peace treaty with the British was signed in Ghent, Belgium. It took time for the message to reach him so he soldiered on until he heard the news. The flash from a supernova exploding in the Milky Way travels at the speed of light, but there is a similar lag as information travels across a great distance: there are many supernova explosions in the Milky Way for which we haven't yet seen the light. Supernovae



THE MILKY WAY
(Detail)

Figure 1.3. In 1917, Einstein was advised that the Milky Way was the Universe. Mistaking a part for the whole is common with large entities. Copyright © 2002 The New Yorker Collection from cartoonbank.com. All Rights Reserved.

erupt every 100 years or so in a galaxy like ours. Since the light from a supernova might take 20,000 years to travel to us, light from hundreds of supernovae in our own galaxy is on the way to us now, the flash from each one a growing shell traveling outward at the speed of light, like a ripple in a still pond from a fish leaping at twilight. Will one of those little waves lap up on our shores tonight? Will we get to see a supernova in our own galaxy, the way Tycho Brahe, the world's last great observer before the invention of the telescope, did in 1572? We don't know. We *can't* know, since no information travels faster than light to give advance warning. The last really bright supernova was seen in 1987—not in our galaxy, but in our southern neighbor, the Large Magellanic Cloud. Personally, I am ready for another one.

Individual stars are very small compared to the distances between stars, but galaxies are not so tiny compared to their separations. If you imagine a scale model where a star like the sun has the size of a pea, neighboring stars would be 100 miles away. Since



Figure 1.4. The spiral galaxy pair NGC 2207 and IC 2163. Distances between galaxies are not always large compared to the sizes of galaxies. These two are colliding. Note the absorption of light from one galaxy by dust lanes in the other. Courtesy of NASA and the Hubble Heritage Team (STScI/AURA). (Also see color insert)

stars are so small compared to the distances between them, they rarely collide and our galaxy seems a spacious place with a dark sky. But the distances between galaxies, although a million times bigger than the distances between stars, are not so big when compared to the galaxies themselves. If you imagine our galaxy as a dinner plate, then our nearest big neighbor galaxy, the Andromeda galaxy (also known as M31, from its place in the Messier catalog of fuzzy objects), would be just ten feet away, at the other end of the Thanksgiving tablecloth down by Uncle Bill. As galaxies move under their mutual gravitational pull, it is not rare for them to collide and possibly merge. But galaxies undergo a strange sort of collision, quite different from two plates smashing together near the gravy boat, because the individual stars that make up each galaxy are still quite unlikely to hit one another. In about 5 billion years, the Milky Way where we live and M31, now a little over 2 million light-years away but heading our way, will collide. The individual stars will miss one another, like intersecting swarms of bees.

Galaxies are distributed throughout the observable universe, with typical separations of a few million light-years. They are quite gregarious, forming loose groups and dense clusters where the galaxies crowd together, leaving large voids a few hundred million light-years across where galaxies are rare. The Milky Way is in a

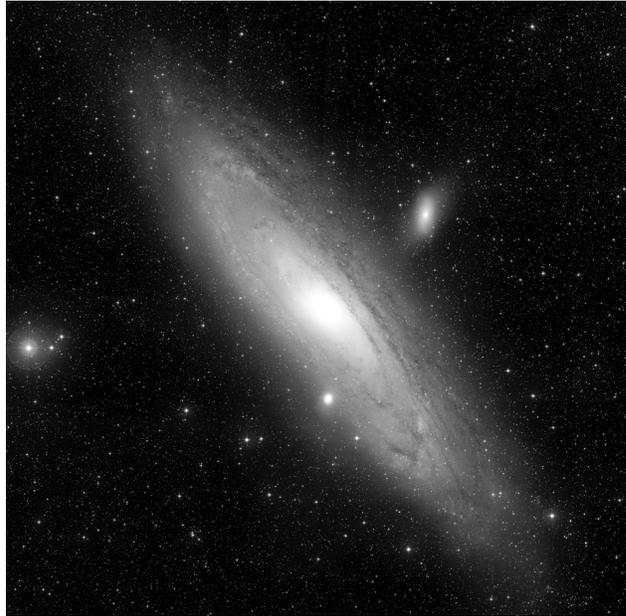


Figure 1.5. The nearby spiral M31. M31 is part of the Local Group of galaxies. In the 1920s, Hubble observed individual cepheid variable stars in this spiral galaxy that showed it was too distant to be part of the Milky Way and must be a distant system as about as big as the Milky Way. Courtesy of P. Challis, Harvard-Smithsonian Center for Astrophysics from the Digital Sky Survey.

small group we call the Local Group that includes the Large and Small Magellanic Clouds, M31, and M33 (another nearby spiral galaxy), among others. The nearest moderate-sized cluster of galaxies is in the direction of the constellation Virgo and dubbed the Virgo Cluster. Judging distance from the apparent brightness of stars in those galaxies as seen with the Hubble Space Telescope, Virgo Cluster galaxies are located about 50 million light-years away. With a small telescope at a site with a dark sky, it's no problem at all to see these and still more distant galaxies whose light was emitted when dinosaurs still roamed the Earth.

The limit of present-day observation is the image of the “Hubble Deep Field,” produced by adding up 342 images taken over 10 days at the end of 1995 with the Hubble Space Telescope. These hours of staring at a very small blank spot in the northern sky have produced

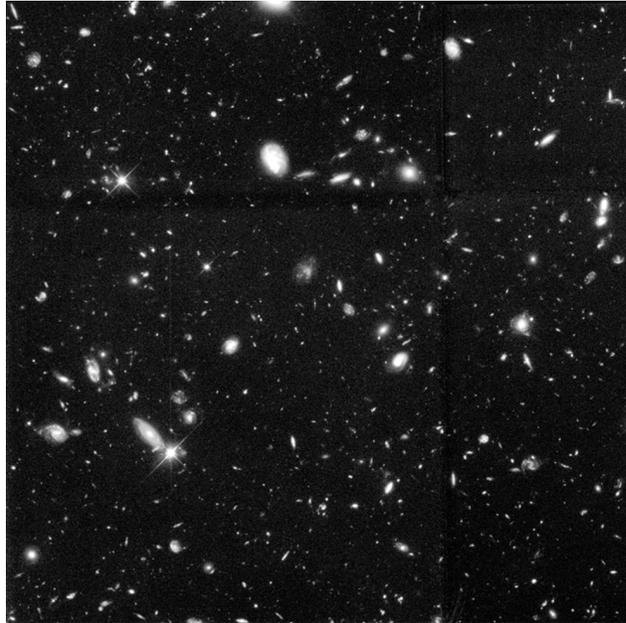


Figure 1.6. The Hubble Deep Field. Composed from 342 images taken over 10 days at the end of 1995, the Hubble Deep Field represents the limit of present methods for observing faint, distant, and young objects. Almost every dot and smudge in this picture is a galaxy, with light from the most distant ones traveling 12 billion light years to reach us. Courtesy of R. Williams/NASA/STScI/AURA. (Also see color insert)

our deepest image of the past. HST is in orbit above the Earth's atmosphere, so it can make images that are not blurred by the ever-changing air. But it is a relatively small telescope, only $1/16$ the area of the biggest ground-based instruments, so the Space Telescope takes a long time to gather light from faint and distant galaxies. Almost everything in the Hubble Deep Field image is a galaxy. Galaxies in the foreground overlap with galaxies in the background until the Hubble Deep Field begins to show wall-to-wall galaxies. The Hubble Deep Field is the ultimate in imaging with today's technology, taking us back to the deepest accessible strata of cosmic history, within about 2 billion years of the Big Bang.

I still can call up the sharp pang of disappointment I felt at age 12 when I was working my way through the big fat volume of *The Complete Sherlock Holmes*. When Holmes walked down the

path at the Reichenbach Falls for his deadly encounter with Moriarty, I felt a boyish sadness at the demise of the best and wisest man Dr. Watson (and I) had ever known. But worse was the feeling, “Is that all there is?”

And in a funny way, the Hubble Deep Field evokes a little of the same feeling. Is that *it*? Is that as far as we can see? Since we have plausible reasons to think the universe is about 14 billion years old, then the most distant thing we could possibly see emitted its light 14 billion years ago. In other words, the finite time since the Big Bang and the finite speed of light place a natural limit to our direct knowledge of the universe—the patch we could possibly observe is only 14 billion light-years in radius. Photons from some objects in the Hubble Deep Field were emitted about 12 billion years ago. So, is that *it*? Have we reached the edge of knowledge (or at least 12/14 of the edge of knowledge)?

In the same way, it is a little deflating to live in such a small and cramped universe. If the typical distance between galaxies is a few million light-years, then if each galaxy were the size of a dinner plate on a holiday table, we would reside in an observable universe only 20 miles in each direction. The observable universe seems more like crowded, jostling Hong Kong than the big sky country of Montana.

Yet *The Complete Sherlock Holmes* had another three-inch thickness of pages I had not read. This should have been a hint that Conan Doyle would relent and that there was much more Sherlock to enjoy. In the same way, a moment's thought shows there is much we have not yet read in the cosmic text. The Hubble Deep Field image was observed in colors of light that span just a slightly broader range than our eyes can see. But as we look deeper to see more distant galaxies and supernovae, still earlier in cosmic time, the light emitted from the first generation of objects in the universe would have been stretched by cosmic expansion right out of the Space Telescope's view and out into infrared wavelengths.

It's as if we have come in late to a movie. I hate that feeling. We've missed the coded messages of the opening titles and all the important early action—in the universe that's the origin of the expansion, the freezing out of helium, then the formation of the

very first objects, the explosions of the very first stars, and the beginning of chemical change that makes the rich and varied world we live in, including the carbon, oxygen, calcium, and iron of our bodies. Much of this action took place even farther in the past than we can hope to see with instruments that operate at the visible wavelengths where our eyes work, Earth's atmosphere is transparent, or where HST has done most of its work.

HST is not looking in the right way to see the very first light from objects in the early universe. If we want to see the opening sequence, we will need to build an equivalent of the HST that works at longer wavelengths, in the infrared: the next-generation space telescope. And we are.

If we want to see the glow of the Big Bang itself, we need to look at even longer wavelengths of light, out where radios work but none of our senses do. And, since 1965, we have been doing that, too. But most of the universe is invisible, even with all our technical means. We know it is there because we see its effects, but we cannot measure it directly. The universe we see is controlled by the universe we do not see: dark matter that is not like the neutrons and protons that make up our bodies, and an enigmatic dark energy that shows itself in the runaway expansion of the universe.

We can build a coherent picture of the universe through astronomical observation and physical theory. Both are hard work, with many false steps, long periods of drudgery, and brief flashes of excitement. Science is not a vast encyclopedia, it is a thin flame of reason burning across ample reservoirs of ignorance. Discovering how the world works is an adventure. We may be brief and we may be short, but we are lucky enough to be here at a moment when technical advances bring new light to old human questions about the past and future of the universe. Supernovae form our method of inquiry, the dark energy is our quarry. The game's afoot!