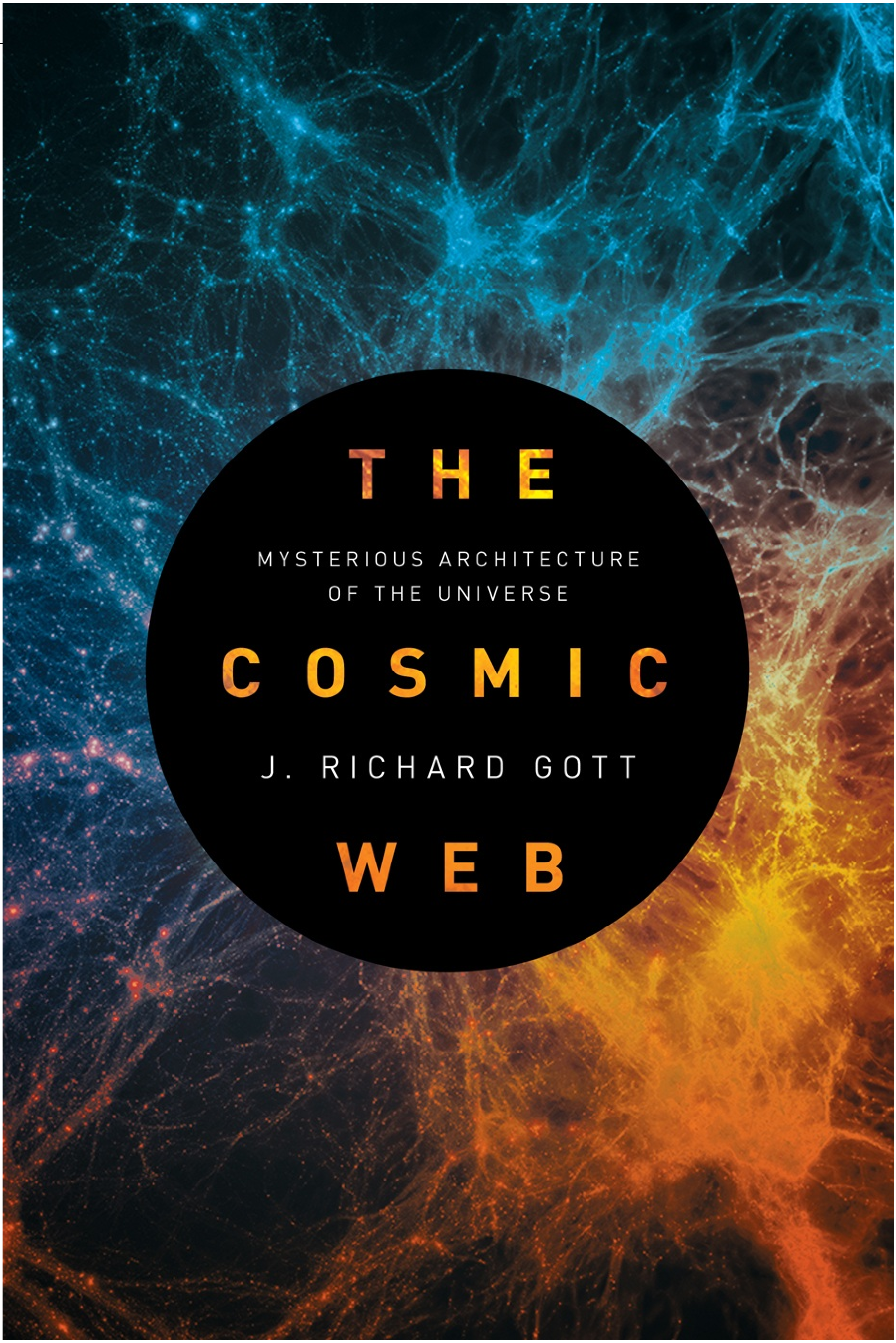
THE
MYSTERIOUS ARCHITECTURE
OF THE UNIVERSE
COSMIC
J. RICHARD GOTT
WEB

The Cosmic Web

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Mysterious Architecture of the Universe

J. Richard Gott

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To Mrs. Ruth Pardon, my high-school math teacher; Dr. Bruce Wavell, head of the Rollins College summer math program; Mrs. Dorothy Schriver, Science Talent Search Program Manager; Drs. James E. Gunn and Martin Rees—who all set me on m way; and to my colleagues in the topology group, who accompanied me on our journey through the cosmic web. Finally, to my new granddaughter Allison—welcome to the universe.

Contents

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Preface

Galileo once said: “Philosophy [nature] is written in that great book which ever is before ou eyes—I mean the universe.... The book is written in mathematical language, and the symbo are triangles, circles and other geometrical figures.” So it proved to be with the arrangeme of galaxies in the universe. To understand it would require geometrical language.

When I was 18 years old, I discovered a group of intricate, spongelike structures made o triangles, squares, pentagons, or hexagons—some of which neatly divided space into tw equal and completely interlocking regions. These were regular spongelike polyhedrons- figures composed of regular polygons whose arrangement around each vertex was identica Being a teenager, when confronted with the ancient Greek wisdom that there were five, an only five, regular polyhedrons (the tetrahedron, cube, octahedron, dodecahedron, an icosahedron)—and that this had been proven long ago—I said, “Well, maybe not.” I made th my highschool science project and took it to my local science fair in Louisville, Kentuck Surprisingly, this would later play a role in my own path to understanding the arrangement o galaxies in the universe.

Johannes Kepler was my inspiration. He had also questioned the ancient wisdom of th five regular polyhedrons. Kepler thought that the three regular polygonal tilings of the plan should be counted as polyhedrons also: the checkerboard, the hexagonal chicken-wire patter and triangles, six around a point, filling the Euclidean plane. Both the checkerboard and th cube were equally regular arrangements of polygons (even though one turned out flat and th other, three-dimensional). Kepler thought a checkerboard, for example, could be considered new regular polyhedron—with an infinite number of faces. But Kepler didn’t stop there; h also recognized two new regular *starred* polyhedrons. One has faces that are five-pointed sta like those on the American flag. Isn’t a star just as regular as a pentagon? It has five point just like the pentagon, and is likewise made by drawing five equal-length lines connectin them. The only difference is that the lines are allowed to cross through each other! You ju have to expand your mind a little to see five-pointed stars as regular. Kepler would take fiv pointed stars as the faces of his new regular polyhedron. He had them cross through eac other to form a three-dimensional star. Kepler understood that you could find new things b breaking the rules just a little. (See Color Plate 1.)

Kepler was also fascinated with how one might use polyhedrons in astronomy. There we six known planets in his day. If you built a set of spheres whose radii marked the distances o each from the Sun, you would have six nested spheres. He thought that you might fit the fiv previously known regular polyhedrons between each of these spheres to explain the geomet of the solar system. In this he was wrong. And when more planets were discovered, the ide broke down completely. But when Kepler was told planets must have circular orbits, h thought to use elliptical orbits instead, and in this he was famously right.

But would my spongelike polyhedrons—which had geometries like a marine sponge, wi many holes percolating through them—remain a mathematical fantasy, or would they eve have any practical application in real-world astronomy? It turned out they had an applicatio in understanding galaxy clustering.

Edwin Hubble discovered that our Milky Way galaxy containing 300 billion stars was n alone in space. There were countless other galaxies just as big as ours. Furthermore, th whole assembly of galaxies was expanding, as I describe in Chapter 1. But how exactly a these galaxies arranged in space? It was a puzzle that confronted astronomers. Galaxi congregated in clusters. Chapter 2 tells how Fritz Zwicky famously studied this at Caltec His work led American cosmologists during the Cold War to adopt a meatball model in whic the high-density clusters floated in a low-density sea, as described in Chapter 3. But th Russian school of cosmology favored a model where galaxies traced a giant honeycomb space with large empty isolated voids. This was a Swiss cheese universe (Chapter 4). I foun that the new theory of inflation[1] (Chapter 5) was inconsistent with either of these pictur and required a spongelike structure in which great clusters of galaxies were connected b filaments of galaxies and great voids were connected to each other by low-density tunne (Chapter 6).

Considering the theory of inflation and remembering those polyhedrons from my youth, wrote a paper with Adrian Melott (University of Kansas) and Mark Dickinson (Princeto University) predicting that galaxies must be arranged on a giant cosmic sponge. The effor we made to verify this prediction became part of the larger story of how teams of observe embarked on heroic efforts to map the universe, as described in Chapters 7, 8, and 9. Thes studies would give us vital insight into how the universe began. Astronomers began to cha the distribution of galaxies in space. Just as cartographers of the past mapped Earth, thes cosmic cartographers began mapping our universe. Starting with surveys of a thousan galaxies, major surveys have now grown to encompass well over a million galaxies. Thre dimensional maps of the galaxies' distribution have now been made, and the structure the reveal has indeed proved to be spongelike. Great clusters of galaxies are connected b *filaments*, or chains of galaxies, in a spongelike geometry, while the low-density voids a connected to each other by low-density tunnels; this entire structure is now called the *cosm web*. Fantastic filamentary chains of galaxies connecting great clusters have been foun stretching over a billion light-years in length. These are the largest structures in the univers Measuring one of them, called the Sloan Great Wall, landed Mario Jurić and me in th *Guinness Book of Records*—and we didn't even have to collect the world's largest ball twine! I will explain how these largest structures in the universe arose as the great expanded fossil remnants of microscopic random quantum fluctuations in the early univers produced by inflation in the universe's first 10^{-35} seconds. This is supported by study of th fluctuations in the cosmic microwave background radiation left over from the universe's fir moments (Chapter 10).

Not only do these structures illuminate the early universe, but they can also be used forecast our future, as described in the final chapter. Will the universe keep expandi exponentially forever, as some models suggest, or will it ultimately coast along in a slowe fashion? Or, will the universe end catastrophically with a Big Rip singularity in the next 15 billion years? A careful study of the cosmic web can help answer these question Distinguishing among these possible alternative futures is one of the highest-priority areas research in astronomy today.

Ranging from a humble high school science project to mapping projects involvi hundreds of astronomers, this book will give you a window on how scientific research done. It is a story of how unexpected connections can lead to new insights and how comput simulations combined with giant telescopic surveys have transformed our understanding the universe in which we live. This is a semiautobiographical account focusing on m adventures but also emphasizing many of the people whose seminal ideas have influenced th field. I have had the good fortune to work with some of the greatest astronomers of ou generation, investigating many of the aspects of this story in one way or another, from galax clustering, gravitational lensing, computer simulations, and mapping large-scale structures inflation and dark energy. This book is told from my personal perspective as I meandere through the complicated web of talented people who fought for and finally won a understanding of how the universe on large scales is arranged. A cosmic web, if you will.

J. Richard Gott
Princeton, New Jersey

The Cosmic Web

Chapter 1

Hubble Discovers the Universe

It is fair to say that Edwin Hubble discovered the universe. Leeuwenhoek peered into h microscope and discovered the microscopic world; Hubble used the great 100-inch-diamet telescope on Mount Wilson in California to discover the macroscopic universe.

Before Hubble, we knew that we lived in an ensemble of stars, which we now call th Milky Way Galaxy. This is a rotating disk of 300 billion stars. The stars you see at night a all members of the Milky Way. The nearest one, Proxima Centauri, is about 4 light-yea away. That means that it takes light traveling at 300,000 kilometers per second about 4 yea to get from it to us. The distances between the stars are enormous—about 30 million stell diameters. The space between the stars is very empty, better than a laboratory vacuum o Earth. Sirius, the brightest star in the sky, is about 9 light-years away.

The Milky Way is shaped like a dinner plate, 100,000 light-years across. We are located this thin plate. When we look perpendicular to the plate, we see only those stars that are ou next-door neighbors in the plate; most of the stars in these directions are less than a fe hundred light-years away. We see about 8,000 naked-eye stars scattered over the entire sk these are all our nearby neighbors in the plate, a tiny sphere of stars nestled within the th width of the plate. But when we look out through the plane of the plate we see the soft glo of stars that are much farther from us but still within the plane of the plate. They trace great circle 360° around the sky. Here we are seeing the circumference of the giant pla itself, as we look around the sky in the plane of the plate. We call this band of light the Mil Way. When Galileo looked at this band of light in his telescope in 1610, he found its fai glow was due to a myriad of faint stars—faint because they are so distant. With the nake eye we can see only their combined faint glow; we cannot resolve that glow into individu stars. It took a telescope to do that. For a long time, this constituted the known universe. O galaxy appeared to be sitting alone in space—an island universe.

In 1918 our idea of our place in the universe started to change. Harlow Shapl discovered that the Sun was not at the center of the Milky Way but instead was abo halfway out toward the edge. We were off center. Shapley felt like the new Copernicus. Ju as Copernicus had moved Earth from the center of the solar system and properly placed th Sun at its center, Shapley moved the solar system from the center of the Milky Way to place in its suburbs. Our position in the universe was looking less and less special. Shapley monumental work did revolutionize our thinking about our place in the universe. He had right to suppose that he had made what would be the most important discovery in astronom in the twentieth century. *Time* would later put Shapley on its cover, on July 29, 193 Shapley was the dean of American astronomers. But his great discovery of 1918 was soon be eclipsed—twice—by Hubble.

Hubble studied the Andromeda Nebula, which had been thought by many, includin Shapley, to be a gas cloud within the Milky Way. The word *nebula* comes from the Lat *nubes*, or “cloud,” denoting the fuzzy appearance of these objects. By careful observatio with the new 100-inch telescope, Hubble discovered that Andromeda was actually an enti galaxy roughly the size of the Milky Way and very far away. Furthermore there were man other similar spiral-shaped nebulae seen in the sky, and these were *all* galaxies like our Milk Way! He classified galaxies by their shapes—elliptical, spiral, and irregular—like som botanist classifying microbes. He observed in different directions and counted the number galaxies he found. There seemed to be an equal number in different directions. On the large scales the universe was homogeneous. There were fainter galaxies further and further awa We were just one galaxy in a vast universe of galaxies. This would have been discove enough, but Hubble was not finished. He measured the distances to these galaxies. Fro spectra of these galaxies he could measure their velocities. He found that the further away galaxy was, the faster it was moving away from us. The whole universe was expanding! Th was astonishing. Isaac Newton had a static universe. Even Einstein, genius of curve spacetime, thought the universe must be static. The discovery that the universe wa expanding was quite simply, astounding. It caused Einstein to revise his ideas about his fiel equations of general relativity—to backtrack on the changes he had made in them to produ a static cosmology. The expansion of the universe has profound implications.

If the universe were static, as Newton and Einstein had supposed, then it could b infinitely old. It would always have been here. This avoided Aristotle’s problem of first caus If the universe had a finite age, however, then *something* must have caused it. But wh caused *that*? Unless one is willing to accept an infinite regression of causes, there must be first cause—but the question remains: what caused the first cause? An expanding univers brought this question back into play. If you played the tape of history backward, you woul see all the galaxies crashing together in the past. There must have been something to start a this expansion—a Big Bang—that began the universe. We now know this occurred 13.8 billio years ago. What caused this Big Bang? Astronomers following Hubble would work on that.

Hubble was the most important astronomer in the twentieth century. *Time* magazine p him on its cover on February 9, 1948. Behind him was a picture of the Palomar Observator whose new 200-inch-diameter telescope could extend Hubble’s observations. He was the fir person to observe with that telescope. Later *Time* would select Hubble as one of the 100 mo influential people in the twentieth century (the only astronomer so honored). Despite th acknowledged importance of his discoveries, Hubble failed to get the American Astronomic Society’s highest award, the Russell Lectureship, given each year to an outstanding Americ astronomer for lifetime achievement. It reminds one of the Nobel Prize committee’s failure t award the Nobel Prize in Literature to Leo Tolstoy, even though they had several chances t do so before he died. The greatest people are often controversial. As with mo groundbreaking discoveries, the whole story is more complicated, and interesting, than ju the simple outline I have given so far. So let’s look into the story in more detail.

Shapley Blazes the Trail

Harlow Shapley had measured the position of the Sun in the Milky Way by using globul clusters. He measured their distances using RR Lyrae variable stars as objects of standar luminosity—*standard candles*. RR Lyrae stars are 40 to 50 times as luminous as the Sun and s can be seen out to fairly large distances. They all have about the same intrinsic *luminosity*, th same wattage as lightbulbs, if you will. (The Sun, for example, has a luminosity of 4 × 10 watts—equal to 4 trillion-trillion 100-watt lightbulbs.) If you saw an RR Lyrae star, you cou figure out how far away it was by seeing how faint it appeared to be in the sky. It's lik seeing a row of standard street lights extending down a street. They all have the sam intrinsic luminosity, but the most distant ones will be fainter than the nearby ones.

Light emitted from a star spreads out in all directions, creating an ever-expanding sphe of light. Let's say you are 1,000 light-years from a star. The light that is passing you from th star is a spherical shell with a radius r of 1,000 light-years. The area of that sphere is $4\pi r^2$, o about 12 million square light-years. If you were 2,000 light-years away, the light would b diluted over an area of $4\pi r^2$ or $4\pi \times$ (2,000 light-years)^2—about 4 × 12 million square ligh years. The new sphere is twice as big as the one before and has an area 4 times as great. Th means that your detector—let's say your 200-inch-diameter telescope—will intercept ¼ a much radiation from the star as it would if it were only 1,000 light-years away from the sta If you are twice as far away, the star appears ¼ as bright. Brightness is measured in watts pe square meter falling on your detector. Brightness diminishes like one over the square of th distance, a fundamental relationship called, not surprisingly, the *inverse-square law*.

Shapley could take repeated pictures of globular clusters of stars. A globular star clust orbiting within the Milky Way would contain over 100,000 stars orbiting about the cluster center of mass, like bees around a hive. Stars whose brightness varied from picture to pictu could be identified as variable stars. Shapley could measure these stars' brightnesses as function of time. He could recognize RR Lyrae variables by their periods of oscillation (th length of time between peaks in brightness, characteristically less than a day) and the amplitude of oscillation (the factor by which their brightness changed from brightest t faintest). Shapley could look at a particular RR Lyrae star and know its intrinsic luminosit This was invaluable. Knowing its intrinsic luminosity, he could measure its appare brightness in the sky and calculate its distance. The fainter it was, the farther away it wou be. By measuring the apparent brightness of the RR Lyrae variables in a globular cluste Shapley could measure the distance to the globular cluster itself. For more distant globul clusters, he used the brightness of the brightest stars in the cluster as a distance indicator, an for the most distant globular clusters, he used the clusters' angular sizes to estimate the distances: a cluster half the angular size was twice as far away.

Shapley measured the distances to many globular clusters, which orbit the center of th Milky Way galaxy in a nearly spherical distribution along paths that take them far above an below the flat "dinner plate" where most stars lie. Looking out above and below the galact plane allowed him to find globular clusters at great distances, free of the confusing obscurin effects of interstellar dust in the plane itself. Shapley found that the 3D distribution o globular clusters in space was off-center relative to Earth. This result was puzzling: thes globular clusters were orbiting the center of the Milky Way and should be centered on it, y Shapley found more globular clusters (and ones that were further away) on one side of th sky than on the other. The distribution of globular clusters seemed centered on a point in th

direction of the constellation of Sagittarius about 25,000 light-years away. This point marke
the center of the galaxy. Shapley had shown that *we* were not at the center of the Milky Wa
—but rather our solar system was about halfway between the center and the outer edge. Th
showed that the Sun was not at a special location at the center of the galaxy.

In 1920 Shapley had a famous debate with Heber Curtis about the nature of the spir nebulae. In the period from 1771 to 1781 Charles Messier had made a catalog of nebula Through a small telescope they look like softly blurry patches of light and can be confuse with comets. Messier was a comet hunter and wanted to make sure he didn't mistake thes objects for new comets, so he took special note of them and cataloged them. These blurr objects actually include a number of different types of things. Some Messier objects (labele by an M followed by their number in the catalog) are supernova gas ejecta (like the Cra Nebula M1) and some, like the Dumbbell Nebula (M27), are gas shed during the process of star collapsing to form a white dwarf. Some are globular clusters (like M13), some are loo star clusters like the Pleiades (M45), many are gas clouds (star-forming regions) in the Milk Way, like the Orion Nebula (M42), and many more are actually external galaxies, lik Andromeda (M31), the Pinwheel (M101), the Whirlpool (M57), M81, M87, and so on. Th spiral nebulae, such as M31, M57, M81, and M101, were the subjects of the Shapley-Curt debate. Their spiral shapes made them look somewhat like hurricanes seen from space. The had spiral arms winding outward from the center—like a pinwheel. Sometimes they we seen face-on, where they showed off circular shapes, and sometimes they were seen near edge-on, looking like dinner plates seen from the side. Were these gas clouds within th Milky Way or were they external galaxies like our own seen at great distances? Shaple maintained that they were gas clouds within the Milky Way. Curtis maintained they we external galaxies just like our own.

The proposals of famous astronomers and philosophers of the past came into the mix. Th ancient Greek philosopher Democritus proposed that the band of light known as the Milk Way could actually be the light of distant stars (right idea—and in about 400 BC!). This ide would be confirmed by Galileo when he turned a telescope to the heavens. In 1750 Thoma Wright speculated that the Milky Way was a thin sheet of stars (right) but thought this wa really part of a large, thin spherical shell of stars orbiting a dark center (wrong). Thus from great distance he thought our galaxy should resemble a sphere of stars, a round blurry blo Then he proposed that many of the faint nebulae we saw were entire galaxies like our ow (right!). In 1755 William Herschel (the discoverer of Uranus) designated a subclass of nebula he called "spiral nebulae." That same year the preeminent philosopher of his day, Immanu Kant, proposed that the spiral nebulae were actually galaxies like our own seen at gre distances—he called them "island universes." Curtis had these ideas on his side.

Shapley spent most of the time defending his recent determination of the enormous size the Milky Way; he thought this result would make the predicted distances to the spir nebulae seem ridiculously large if they were to be objects comparable to the Milky Way size. Some novae (stars that suddenly flare in brightness by a large factor without explodin were observed in spiral nebulae, and these had brightnesses comparable to other novae in th Milky Way, placing them firmly within our galaxy. Curtis mentioned this point again himself. But in fact, these were *supernovae*, not novae at all but vastly more luminous stell explosions that were actually just as far away as Curtis needed. Curtis's best argument cam from noticing that the spectra of the spiral nebulae looked like the spectra of star cluster not those of gas clouds. The debate ended inconclusively. Most people in the audien probably left with the same views they had when they entered. In science, such questions a not settled by debates or by who scores more oratorical points. They are often settled by ne and decisive data—which Hubble would soon be perfectly positioned to supply.

Hubble Changes the Game

Like most people who make important contributions, Hubble was blessed with both tale and luck. Born in Marshfield, Missouri, in 1889, Hubble held the high school high-jum record for the state of Illinois. He attended the University of Illinois and later went to Oxfo as a Rhodes Scholar. Rhodes scholarships rewarded athletic as well as academic prowes When he returned from England, he spent some time in my hometown of Louisvill Kentucky, living for part of that time in a quiet, genteel area of Louisville called t Highlands, where my mother and grandmother once lived. Hubble followed his father wishes that he study law, but after his father's death, he turned to his true interests science. He was a high school teacher for a while before going to graduate school at t University of Chicago, where he earned his PhD in astronomy; for his thesis research, he too photographs of faint nebulae. Here he had mastered the skill that would be needed to sett the Curtis-Shapley controversy. After a brief period of service in World War I, he returned get a staff position at Mount Wilson. He was hired by George Ellery Hale. His good fortu was compounded. Yerkes Observatory, where he had done his doctoral work, possessed t largest refracting telescope in the world with a diameter of 40 inches. This was and st remains the largest refracting telescope ever built. It had a lens at the front, which broug light to a focus at the back, where an eyepiece was placed to view the image. Galileo's fir telescope was a refracting telescope whose lens had a diameter of 1.46 inches. With this was able to resolve stars in the soft band of light called the Milky Way. The Yerkes telesco was 40 inches in diameter, or 27 times as large in diameter. A lens is like a bucket to cat light, with a light-gathering power proportional to its area. (Put a bucket out in the rain; if has twice the diameter, its opening area will be four times as large and will collect four tim as much rain.) The Yerkes telescope had 27 × 27, or 729, times the light-gathering power Galileo's telescope. Since brightness falls off like the square of the distance, it should be ab to discern stars 27 times more distant than those Galileo could see. Furthermore, lo exposures using film gathered light over time and were more sensitive than the human ey Hubble was by now an expert at taking just these kinds of pictures.

Now George Ellery Hale—telescope builder par excellence—enters. Hale, who had bu the 40-inch Yerkes telescope, was just now finishing construction of the largest telescope ev —a reflecting telescope 100 inches in diameter—on Mount Wilson. A telescope with a 4 inchdiameter lens was about the largest of that type you could build. The lens had to supported around its edge and began to sag in the middle if it was too big and heavy. But reflecting telescope of the type invented by Isaac Newton let light come in the front and hit big mirror in the back, where it was reflected back toward the front again. The light cou then be directed via a small secondary mirror to a focus outside the tube where you wou put the eyepiece. The big mirror was supported on its entire back surface and thus could larger. The 100-inch-diameter reflecting telescope was 2.5 times the diameter of the Yerk telescope and able to detect individual stars 2.5 times further away. If Galileo could discer individual stars that were 25,000 light-years away in the Milky Way, the 100-inch telescop should be able to detect individual stars 1.6 million light-years away. With the advantage long-exposure photographs, Hubble could extend this distance even farther.

Hubble arrived in Los Angeles in 1919 to take up his new job soon after the 100-inc telescope on Mount Wilson had opened for business. Hubble made good use of his uniq opportunity. He took photographs of the Andromeda Nebula (M31). It was the spiral nebu with the largest angular size in the sky (modern photographs trace its diameter at 3° in th sky—6 times the angular diameter of the Moon.) It was, therefore, a good candidate for th closest spiral nebula. Hubble's photographs resolved it into stars. It was not a gas cloud. looked like a fuzzy patch because it was made of faint distant stars. He made a sequence photographs. Some of the brightest stars varied in brightness in a regular way over time. H could recognize them as Cepheid variables—stars whose luminosity varied periodically ov periods ranging from days to months (and which were considerably more luminous than R Lyrae stars). In 1908 Henrietta Leavitt, working at Harvard College Observatory, discovere a relationship between the period of oscillation of a Cepheid variable and its intrins luminosity. If you saw a Cepheid variable and measured the timescale of its period variation in brightness (in days), you could figure out its intrinsic luminosity (in watts) an therefore determine how far away it was by observing how faint it appeared to be in the sk But the Cepheid variables Hubble found in the Andromeda nebula were *very* faint an therefore *very* far away, far outside the Milky Way Galaxy proper. The Andromeda Nebu was so far outside the Milky Way that given its angular diameter, it had to have a physic size of the same order of magnitude as the Milky Way. The Andromeda Nebula was itself galaxy—just like the Milky Way. The Curtis–Shapley debate had been settled—Shapley wa wrong, and Curtis was proved right. People like Immanuel Kant had speculated with goo reasons that the spiral nebulae might be entire galaxies like our own, but now we knew Hubble's evidence settled the case. It would turn out that Hubble's enormous distanc estimate for M31 was actually an *underestimate*. But it made the point. M31 was indeed fa outside our own galaxy.

The Andromeda Galaxy (M31) is actually 2.5 million light-years away. (I can call it galaxy now rather than a nebula.) It is a disklike system about 120,000 light-years acros Our galaxy, the Milky Way, is a similar disklike system about 100,000 light-years across. our galaxy were the size of a standard dinner plate (10 inches across), the Andromeda Gala (M31) would be another dinner plate 21 feet away. Light from the nearest star that we s today started on its way about 4 years ago. As you look farther away, you look further bac in time. When you look toward the Milky Way's galactic center (in the constellatio Sagittarius) 25,000 light-years away, you are seeing it not as it is now but as it was 25,00 years ago, about the time a child left footprints in the Chauvet Cave in France while viewi the cave paintings there. The light from the Andromeda Galaxy started on its way 2.5 millio years ago, when our grandfather species from the genus *Australopithecus* walked the earth.

How can we visualize such large distances? Models can be helpful. At a scale of 1/billio the entire Earth becomes a marble ½ inch across. A billion is a big number. If Earth is marble ½ inch across, the Moon is a BB ⅛ inch across, located 15 inches away. Fifteen inch at a 1/billion scale is as far as human astronauts have ever gone—just 15 inches. The Sun, this scale, is a beach ball 55 inches across, 500 feet away. The nearest star, Proxima Centaur is a basketball 9 inches across, located 25,000 miles away. That's equal to the enti circumference of Earth, probably more than you drive your car in a year.

Let's shrink things by another factor of a billion, which shrinks Earth to a size small than an atom. At this scale of 1/billion-billion, Proxima Centauri is about the size of hydrogen atom. The typical distance between stars is now about 1.6 inches. Imagine walkin in a heavy snowstorm where the falling snowflakes are a less than a couple of inches apar That is what our region of the Milky Way is like at a scale of 1/billion-billion. Go out night, and you will see a snowstorm of stars. The Milky Way is about 2.5 miles across at th scale—about the size of a town. When we see the band of the Milky Way, we are seeing th distant lights of our town. Andromeda is another town 64 miles away, at this scale. Hubb was finding more and more galaxies stretching as far as telescopes could see. The typic distances between bright galaxies are about 24 million light-years—140 miles apart on ou 1/billionbillion-scale model. Astronomers have seen galaxies as far as 13 billion light-yea away—that's 76,000 miles away in our 1/billion-billion-scale model, in which stars are barel larger than atomic size. We are seeing these most distant galaxies as they were 13 billio years ago. This helps us visualize the vastness of the visible universe.

Slipher's Troublesome Redshifts

Meanwhile, Vesto Slipher was observing at Lowell Observatory in Flagstaff, Arizona, takin spectra of galaxies. Slipher found absorption lines in the spectra he took that were wavelengths associated with particular elements. But he found them shifted slightly fro their laboratory values. This is due to the Doppler shift. If a galaxy is moving toward u succeeding wave crests of light are emitted at locations progressively closer to us as th galaxy approaches, crowding the wave crests together, shortening the wavelength of the ligh Blue light has a shorter wavelength than red light, so this causes a "blueshift" in the spectr lines. If the galaxy is moving away from us, each subsequent wave crest reaching us emitted at locations further and further away, and this stretches out the distance betwee wave crests. It causes a "redshift" in the spectral lines. The *redshift* z is defined as th fractional shift in the wavelengths of the spectral lines of a galaxy from the laboratory value $(\lambda_{\text{observed}} - \lambda_{\text{lab}})/\lambda_{\text{lab}}$. For small redshifts (much less than 1), such as Hubble was observing, z approximately equal to the recessional velocity of the galaxy divided by the speed of ligh (In general, the recessional velocity divided by the speed of light is $[(z + 1)^2 - 1]/[(z$ $1)^2 + 1]$. As the red-shift approaches infinity, the recessional velocity approaches the speed light, according to Einstein's theory of relativity.) We can experience the Doppler effect wit sound waves when a train approaches blowing its whistle. As it approaches, we hear a hig pitch (short-wavelength) sound, and after it passes the pitch becomes lower (long wavelength) as the train moves away: WHEEEEOOOOOOO.

Doppler shifts had already been used to measure the velocities of individual stars in th solar neighborhood. These velocities were on the order of 20 kilometers per second an showed some stars moving toward us and others moving away—not surprising, if these sta are moving with us on slightly different orbits within our galaxy. When Slipher measured th

Andromeda Galaxy, he found a blueshift corresponding to an approach velocity of 30 kilometers per second. This was an enormous velocity, roughly 0.1% the speed of light, muc larger than that of individual nearby stars in our galaxy. Today we know that this hig approach velocity toward the solar system results in part from the fact that the stars in ou solar neighborhood have a mean rotational velocity about the center of our galaxy (about 22 kilometers/second), which happens to be sending us in more or less the direction of wher Andromeda happens to be on the sky. Furthermore, the Andromeda galaxy is actually fallin toward the Milky Way because of their mutual gravitational attraction. By measuring th differential shift in the spectral lines across the face of an individual galaxy, Slipher was th first to prove that the spiral nebulae were rotating. Slipher continued taking spectra o galaxies and found to his surprise that almost without exception (Andromeda being one) the had redshifts. In general, galaxies were moving away from us. In 1917 he published a table o redshifts. The average recessional velocity of the galaxies in his table was 57 kilometers/second. Astonishing—and unexpected. As he looked at ever fainter (more distan galaxies, the average recessional velocity had risen from 400 kilometers/second in 1915 t 570 kilometers/second by 1917. The effect was getting more dramatic. On this basis, Joh Peacock (2013) has argued that Slipher should be given credit for the discovery of th expansion of the universe—because he found so many redshifts, indicating that other galaxie were moving away from us. Peacock has noted that Slipher's redshifts, because they were s large, identified the spiral nebulae as objects outside our galaxy. Slipher did consider the ide that the spiral nebulae might be scattering, but he rejected the notion because they als seemed clustered. Ultimately, Slipher thought galaxies might be moving at high individu velocities edgewise through space, like thrown Frisbees—in that surmise he was incorrec Slipher deduced that the solar system had an individual velocity of about 70 kilometers/second relative to the mean motion of all the galaxies he saw. The modern valu for this is 384 kilometers/second. Slipher's work on redshifts was fundamental and set th stage for what Hubble was able to do later. In addition, as director of the Lowe Observatory, Slipher hired Clyde Tombaugh and started him on the project that would resu in the discovery of Pluto. For his contributions, Slipher was awarded the Gold Medal of th Royal Astronomical Society in 1932.

Einstein Has His Say

Theory enters here. In 1915, after 8 years of concentrated effort, Einstein worked out th correct field equation for his theory of general relativity. This theory explained gravity in revolutionary way, as the result of curved spacetime. Einstein's equation showed how th "stuff" of the universe (matter, energy and pressure) cause spacetime to curve. The right sid of the equation describes the mass-energy density and pressure associated with stuff (matte and radiation) at a point. The left side of the equation tells us how spacetime is curved at th point.[1] Particles follow the straightest trajectories they can in the curved space and time. I the same way, a plane follows a great circle trajectory when traveling between two points o Earth. A plane traveling on a straight-line trajectory from New York to Tokyo will pass ove northern Alaska. Stretch a string taut between the two cities on a globe to confirm this. Th trajectory looks curved on a flat Mercator map of Earth, but on the curved surface of th globe it is the straightest trajectory you can draw—it is called a *geodesic*.

Einstein could then work out the geodesic trajectories of planets. They differed slight from those Newton had found. The planet Mercury no longer followed the simple elliptic (Keplerian) path that Newton's theory of gravity predicted. The effects were largest close t the Sun. Einstein predicted that the elliptical shape of Mercury's orbit should slowly rotate a Mercury continued to circle the Sun. This rotation of the orbit amounted to 43 seconds of a per century. A second of arc is 1/3,600 of a degree—so this is a tiny amount of orbit rotation in a century. Nevertheless, astronomers had already measured just this amount anomalous rotation in Mercury's orbit, an effect that Newton's theory was unable to explai When Einstein did this calculation, he said he was so excited it gave him palpitations of th heart. When his prediction of 43 seconds of arc per century matched the exact amount unexplained rotation astronomers had already observed, he was overjoyed.

Einstein then calculated how much light itself should bend as it passed near the limb the Sun. According to his theory it should be deflected by 1.75 seconds of arc. If particles light were attracted by gravity in the same way that massive particles were in Newton theory, the deflection would be only half that—0.87 seconds of arc. The effect could b tested during a total eclipse of the Sun, when the Moon blocks the Sun's bright surfac allowing background stars to be observed near it. In 1919 Sir Arthur Eddington's Britis expedition took photographs of stars near the Sun during a solar eclipse and compared the with the positions of those stars on photographs taken 6 months later, when Earth had move so the Sun was nowhere near those stars in the sky. Deflections of 1.98 ± 0.30 and 1.61 0.30 seconds of arc were observed during the eclipse from two different locations, agreement with Einstein's value within the observational errors (± 0.30 seconds of arc) an in clear disagreement with Newton's value. Newton's account of gravity was overthrow This was the "play of the century" in science. On the day he learned of the eclipse resul Einstein wrote a touching note to his mother, saying: "Good news today." The results we publicly announced at a joint meeting of the Royal Society and the Royal Astronomic Society. J. J. Thomson (the discoverer of the electron) pronounced the result "the mo important result obtained in connection with the theory of gravitation since Newton's day At that moment Einstein moved up to Newtonian stature. The Einsteinian deflection wa quickly confirmed by W. W. Campbell and R. Trumpler, in the 1922 solar eclipse; they foun a deflection of 1.82 ± 0.20 seconds of arc. Importantly, it has been confirmed with highe and higher accuracy ever since.

In 1916 Karl Schwarzschild found an exact solution to Einstein's equation for a point mas We know this today as the *black hole solution*. In 1917 Einstein applied his equation cosmology. He found he could not produce a static solution. Newton had a static univers stars filling infinite space uniformly, with the gravitational forces on each star on averag canceling out. Such a universe could be infinitely old and escape the question of first caus Einstein in 1917 knew that the individual velocities of stars were small, of order 2 kilometers/second, much less than the velocity of light, and moving randomly. This suggeste to him a static universe. So, he added a term to his field equation of General Relativity.[2] Th new term was called the *cosmological constant*. It preserved the desirable property of th original equations that energy was conserved locally (in small regions), and the new ter was so tiny it did not interfere with the orbit of Mercury or the light bending appreciabl

Primarily, it provided a repulsion term that balanced the average gravitational attraction o the stars for each other, allowing a static model of the universe. In his 1917 paper he argue that such a static model was required because of the small velocities of the stars (relative t the speed of light). These, of course, were just stars in our solar neighborhood in the Milk Way. In the Einstein universe, the volume of space was finite and curved but had no edges. was like the surface of a higher-dimensional sphere called a *3-sphere*. Just as a circle has finite circumference and a sphere has a finite surface area, Einstein's Time 3-sphere univers had a finite volume. If you started off in your spaceship on a voyage in Einstein's stat universe and steered as straight a course as you could, you would return to your home plan after having circumnavigated the entire universe—just as you can circle Earth's surface an return to where you started. Because Einstein's universe was static, its volume wa unchanging with time. Figure 1.1 shows a spacetime diagram of the Einstein static univers It shows the dimension of time vertically, with the future toward the top. One dimension o space is shown horizontally. The Einstein static universe spacetime looks like the surface of cylinder. The static 3-sphere universe is depicted as a circle whose circumference is constan with time. Stack up a bunch of circles (all the same radius) representing the 3-sphere univers at different instants and you get a cylinder. The only thing real in this picture is the cylinde itself. Forget the inside and outside.

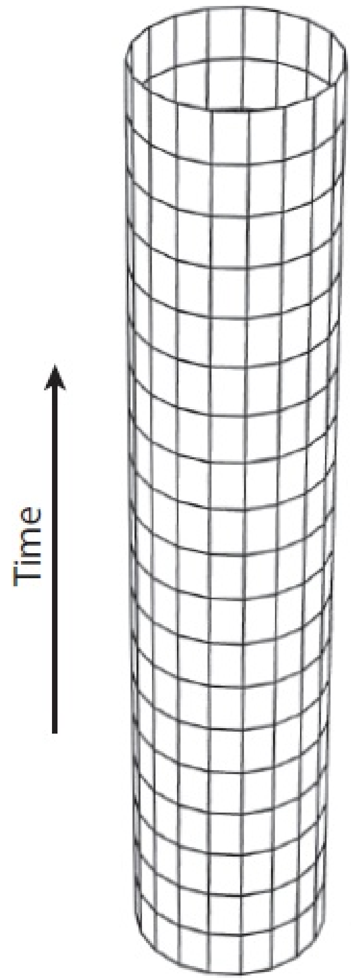

Figure 1.1. Spacetime diagram of the Einstein Static Universe. We are showing only one dimension of space (around the circumference of the cylinder) and the dimension of time (the vertical direction, future toward the top). Worldlines of stars (or galaxies) are straight lines (geodesics) going straight up the cylinder. The circumference represents the circumference o the surface of a higher-dimensional spherical balloon (a 3-sphere) whose radius is unchanging with time. The only real thir is the cylinder itself—the inside and outside have no significance. (Credit: J. Richard Gott, *Time Travel in Einstein's Universe,* Boston: Houghton Mifflin, 2001)

That same year, 1917, Dutch mathematician and physicist Willem de Sitter found an exa solution to Einstein's field equation, including Einstein's new cosmological constant term b having no matter in it at all. This was an empty universe—no stars, no galaxies, just empt curved space. (Why should we be interested in such a universe? Because the real universe of rather low density and so might roughly approximate an empty universe in the limit.) D Sitter's universe looked static as well and seemed to cover only half of a higher-dimension 3-sphere—as if you had cut Einstein's static universe in half and then thrown half of it awa If you sat at the "north pole" of this universe, you could see down only to its "equator." D Sitter proposed that antipodal points in spherical universe be identified as identical points—a if you had a replica of yourself living at the south pole. That way, the universe you sa (north of the equator) really included all the objects in the universe. The de Sitter univers would thus have half the volume of the comparable Einstein static universe. You would se objects that lived closer to the equator aging in slow motion and emitting light waves in slo motion. If their atoms emitted light at a certain frequency, you would see it at a slowe frequency—and a longer wavelength. Thus, in de Sitter space, distant objects showe redshifts. This might explain Slipher's redshifts. These were gravitational redshifts, caused b a photon of light losing energy and increasing in wavelength as it fights its way out of a dee gravitational well. This effect is predicted by general relativity. Clocks on Earth tick a tiny b slowly relative to those in interstellar space. Einstein, in his work on the photoelectric effec showed that electromagnetic waves (light) are composed of photons whose energies ar inversely proportional to their wavelength. When we send a photon into the sky, it lose energy as it climbs against Earth's gravitational field, and its wavelength increases. (GP systems using satellites have to take this effect into account when they calculate you position.)

But de Sitter's static coordinate system was incomplete and gave a false impression. It like the story of a blind man examining an elephant; if he touched only its trunk, he mig pronounce that an elephant was most like a fire hose. Figure 1.2 shows our moder understanding of de Sitter spacetime.

It is a 3-sphere universe that starts off with infinite size in the infinite past, contracts to minimum radius at a “waist” in the center, and then reexpands. It is the gravitational repulsive effect of the cosmological constant that halts the contraction and causes th subsequent expansion. De Sitter spacetime looks like a corset. The waist appears as a circl This represents the circumference of the 3-sphere universe at the time of its minimum siz The “north pole” is the point at the far left edge of this circle. But the north pole is not just point that lasts for an instant. It stays around forever. If you live there, your worldline—you path through spacetime—is the vertical corset stay at the far left. De Sitter's static coordina system, trails after you like a flock of geese following after a leader. The coordinate syster covers only the one quadrant of de Sitter spacetime next to the north pole corset stay.

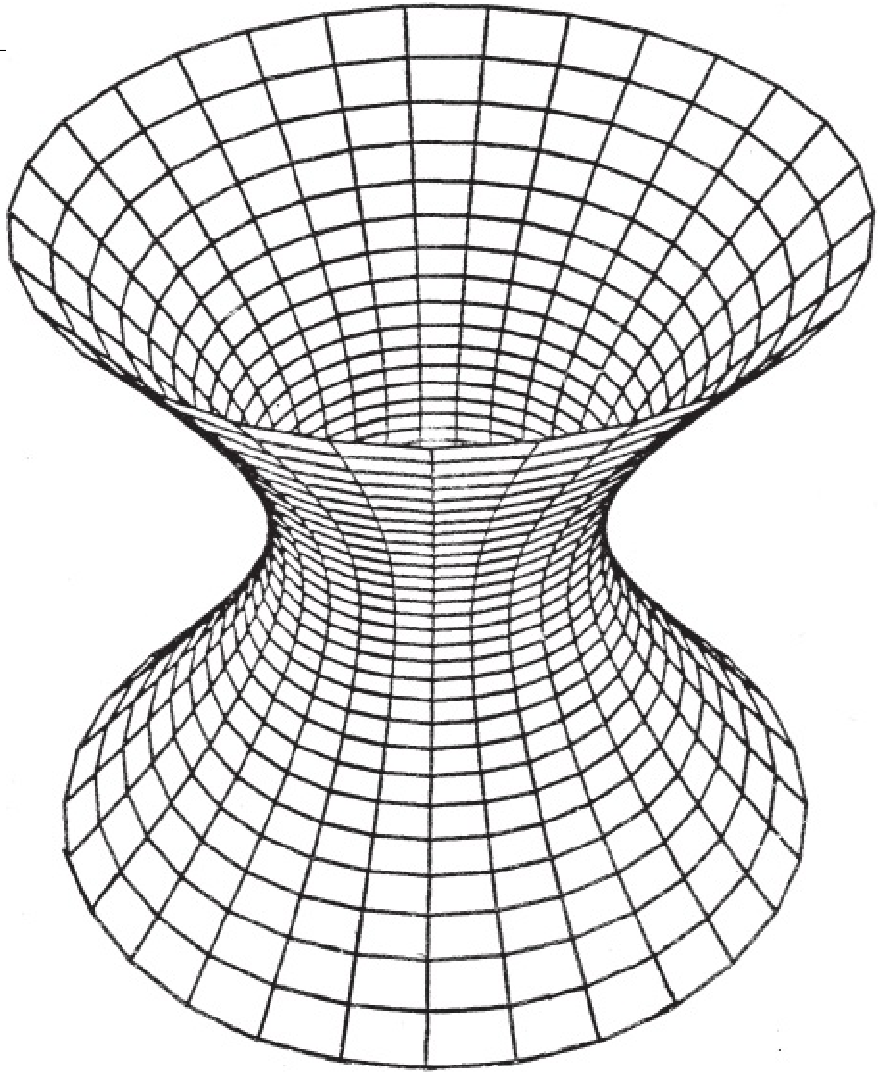

Figure 1.2. Modern understanding of De Sitter spacetime. Diagram shows one dimension of space (around the circumference) and the dimension of time vertically, future toward the top. De Sitter spacetime looks like a corset with a narrow waist at the middle. The horizontal circular cross sections show the size of the 3-sphere universe as it contracts and then expands. The vertical "corset stays" represent possible geodesic *worldlines* (paths through spacetime) of particles. Put a large X through the center of the figure—De Sitter's 1917 coordinate system covered only the left quadrant; leaving out top, bottom, and right quadrants. It made the spacetime look static, but actually it is dynamical, as depicted here. (Credit: J. Richard Gott, *Time Travel in Einstein's Universe*, Boston: Houghton Mifflin, 2001)

Actually, de Sitter space was a complete spherical universe. It was expanding at la times, which caused distant galaxies to have redshifts. It was a strange universe.

Astronomers at that time were asking themselves if de Sitter space was a useful model fo our universe. A piece of Princeton lore (which I heard as a graduate student) was that Henr Norris Russell once asked Harlow Shapley if the Slipher redshifts could be due to the de Sitte effect. No, Shapley reportedly replied, that was impossible, since the globular cluste [Shapley erroneously thought] were at much larger distances than the spiral nebulae, an they showed no redshifts at all! Without proper distances, Shapley found Slipher's redshif did not even convince him that the spiral nebulae were outside the Milky Way.

In 1922, Alexander Friedmann, in Russia, found an exact solution to Einstein's origin equations *without* the cosmological constant. This was a dynamical solution—not static. Lik the Einstein static universe, its shape was the surface of a higher-dimensional sphere—a sphere, but its radius changed with time. It started at zero size with a Big Bang. It the expanded rapidly. Galaxies would be like pennies taped to the surface of a balloon: as yo sample content of The Cosmic Web: Mysterious Architecture of the Universe