



The 4 Percent Universe

DARK MATTER, DARK ENERGY, AND THE
RACE TO DISCOVER THE REST OF REALITY



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HOUGHTON MIFFLIN HARCOURT
Boston New York
2011

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www.hmhbooks.com

Library of Congress Cataloging-in-Publication Data

Panek, Richard.

The four-percent universe : dark matter, dark energy, and the race to discover the rest of reality /

Richard Panek.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-618-98244-8

1. Cosmology. 2. Physics. 3. Astrophysics. I. Title.

QB981.P257 2010

523.1—dc22 2010025838

Book design by Lisa Diercks

This book is typeset in Bulmer, Hydra Text, and Belizio.

Printed in the United States of America

DOC 10 9 8 7 6 5 4 3 2 1

Some passages in this book appeared, usually in different form, in *Discover*, the *New York Times Magazine*, *Sky & Telescope*, and *Smithsonian*.

Portions of [chapter 11](#) are based on work supported by the National Science Foundation under Grant No. 0739893. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

For Meg, with love

"I know," said Nick.

"You don't know," said his father.

—*Ernest Hemingway*

Acknowledgments

THE AUTHOR EXPRESSES deep appreciation to Amanda Cook for her extraordinary editorial guidance as well as her genuine passion for the dark side of the universe; Henry Dunow, who, with his usual wisdom, made the match of editor and author; Katya Rice for her expert eye; Katherine Bouton for taking a chance on science and assigning an article on this subject; the John Simon Guggenheim Memorial Foundation, the National Science Foundation's Antarctic Artists and Writers Program, and the New York Foundation for the Arts for their generous and essential support; and Gabriel and Charlie (who claim to know what dark matter and dark energy are but refuse to tell their father, who loves them anyway).

Prologue

THE TIME HAD come to look inside the box. On November 5, 2009, scientists at sixteen institutions around the world took their seats before their computer screens and waited for the show to begin: two software programs being run by two graduate students—one at the University of Minnesota, the other at the California Institute of Technology—simultaneously. For fifteen minutes the two scripts would sort through data that had been collecting far underground in a long-abandoned iron mine in northern Minnesota. Over the past year, thirty ultrasensitive detectors—deep-freeze cavities the size of refrigerators, shielded from stray cosmic rays by half a mile of bedrock and snug blankets of lead, their interiors cooled almost to absolute zero, each interior harboring a heart of germanium atoms—had been looking for a particular piece of the universe. The data from that search had sped from the detectors to offsite computers, where, following the protocol of a blind analysis, it remained in a "box," out of sight. Just after 9 A.M. Central Time, the "unblinding party" began.

Jodi Cooley watched on the screen in her office at Southern Methodist University. As the coordinator of data analysis for the experiment, she had made sure that researchers wrote the two scripts separately using two independent approaches, so as to further ensure against bias. She had also arranged for all the collaborators on the project—physicists at Stanford, Berkeley, Brown; in Florida, Texas, Ohio, Switzerland—to be sitting at their computers at the same time. Together they would watch the evidence as it popped up on their screens, one plot per detector, two versions of each plot.

After a few moments, plots began appearing. Nothing. Nothing. Nothing.

Then, three or four minutes into the run, a detection appeared—on the same plots in both programs. A dot on a graph. A dot within a narrow, desirable band. A band where all the other dots weren't falling.

A few minutes later another pair of dots on another pair of plots appeared within the same narrow band.

And a few minutes later the programs had run their course. That was it, then. Two detections.

"Wow," Cooley thought.

Wow, as in: They had actually seen something, when they had expected to get the same result as the previous peek inside a "box" of different data nearly two years earlier—nothing.

Wow, as in: If you're going to get detections, two is a frustrating number—statistically tantalizing but not sufficient to claim a discovery.

But mostly Wow, as in: They might have gotten the first glimpse of dark matter—a piece of our universe that until recently we hadn't even known to look for, because until recently we hadn't realized that our universe was almost entirely missing.

It wouldn't be the first time that the vast majority of the universe turned out to be hidden to us. In 1610 Galileo announced to the world that by observing the heavens through a new instrument—what we would call a telescope—he had discovered that the universe consists of more than meets the eye. The five hundred copies of the pamphlet announcing his results sold out immediately; when a package containing a copy arrived in Florence, a crowd quickly gathered around the recipient and demanded to hear every word. For as long as members of our species had been lying on our backs, looking up at the night sky, we had assumed that what we saw was all there was. But then Galileo found mountains on the Moon, satellites of Jupiter, hundreds of stars. Suddenly we had a new universe to explore, one to which astronomers would add, over the next four centuries, new moons around other planets, new planets around our Sun, hundreds of planets around other stars, a hundred billion stars in our galaxy, hundreds of billions of galaxies beyond our own.

By the first decade of the twenty-first century, however, astronomers had concluded that even this extravagant census of the universe might be as out-of-date as the five-planet cosmos that Galileo inherited from the ancients. The new universe consists of only a minuscule fraction of what we had always assumed it did—the material that makes up you and me and my laptop and all those moons and planets and stars and galaxies. The rest—the overwhelming majority of the universe—is ... who knows?

"Dark," cosmologists call it, in what could go down in history as the ultimate semantic surrender. This is not "dark" as in distant or invisible. This is not "dark" as in black holes or deep space. This is "dark" as in unknown for now, and possibly forever: 23 percent something mysterious that they call dark matter, 73 percent something even more mysterious that they call dark energy. Which leaves only 4 percent the stuff of us. As one theorist likes to say at public lectures, "We're just a bit of pollution." Get rid of us and of everything else we've ever thought of as the universe, and very little would change. "We're completely irrelevant," he adds, cheerfully.

All well and good. Astronomy is full of homo sapiens-humbling insights. But these lessons in insignificance had always been at least somewhat ameliorated by a deeper understanding of the universe. The more we could observe, the more we would know. But what about the less we could observe? What happens to our understanding of the universe then? What currently unimaginable repercussions would this limitation, and our ability to overcome it or not, have for our laws of physics and our philosophy—our twin frames of reference for our relationship to the universe?

Astronomers are finding out. The "ultimate Copernican revolution," as they often call it, is taking place right now. It's happening in underground mines, where ultrasensitive detectors wait for the ping of a hypothetical particle that might already have arrived or might never come, and it's happening in ivory towers, where coffee-break conversations conjure multiverses out of espresso steam. It's happening at the South Pole, where telescopes monitor the relic radiation from the Big Bang; in Stockholm, where Nobelists have already begun to receive recognition for their encounters with the dark side; on the laptops of postdocs around the world, as they observe the real-time self-annihilation of stars, billions of light-years distant, from the comfort of a living room couch. It's happening in healthy collaborations and, the universe being the intrinsically Darwinian place it is, in career-threatening competitions.

The astronomers who have found themselves leading this revolution didn't set out to do so. Like Galileo, they had no reason to expect that they would discover new phenomena. They weren't looking for dark matter. They weren't looking for dark energy. And when they found the evidence for dark matter and dark energy, they didn't believe it. But as more and better evidence accumulated, they and their peers reached a consensus that the universe we thought we knew, for as long as civilization had been looking at the night sky, is only a shadow of what's out there. That we have been blind to the actual universe because it consists of less than meets the eye. And that *that* universe is our universe—one we are only beginning to explore.

It's 1610 all over again.

PART I

More Than Meets the Eye

1. Let There Be Light

IN THE BEGINNING—which is to say, 1965—the universe was simple. It came into being one noontime early that year over the course of a telephone conversation. Jim Peebles was sitting in the office of his mentor and frequent collaborator, the Princeton physicist Robert Dicke, along with two other colleagues. The phone rang; Dicke took the call. Dicke helped run a research firm on the side, and he himself held dozens of patents. During these weekly brown-bag lunches in his office, he sometimes got phone calls that were full of esoteric and technical vocabulary that Peebles didn't recognize. This call, though, contained esoteric and technical vocabulary that Peebles knew intimately—concepts the four physicists had been discussing that very afternoon. Cold load, for instance: a device that would help calibrate the horn antenna—another term Peebles overheard—that they would be using to try to detect a specific signal from space. The three physicists grew quiet and looked at Dicke. Dicke thanked the caller and hung up, then turned to his colleagues and said, "Well, boys, we've been scooped."

The caller was an astronomer at the Bell Telephone Laboratories who had collected some curious data but had no idea what it meant. Peebles and Dicke had developed a curious idea but had no data to support it. The other two physicists at lunch had been building an antenna to detect a signal that would offer support for the curious idea, but now, Dicke said, a pair of astronomers at Bell Labs had probably found it first—without knowing what they'd done.

The mood in Dicke's office was not one of deflation or disappointment. If the four of them had in fact been scooped, they had also been vindicated. If the caller was right, then they too were right, or at least heading in a potentially profitable scientific direction. If nothing else, they could take some comfort from the possibility that they were the first persons in the history of the world to understand the history of the universe.

But before reaching any conclusions, they would have to check the data for themselves. Dicke and two of the other Princeton physicists soon drove the thirty miles to Holmdel Township, New Jersey, home of the Bell Labs research center. The Bell Labs astronomers—Arno Penzias, who had placed the call to Dicke, and his collaborator Robert Wilson—took them to see the antenna. It was a horn-shaped instrument, as big as a boxcar, by the side of a private road at the top of Crawford Hill, the highest point for miles around. After the five of them had squeezed into the control cab, their elbows brushing vacuum tubes and instrument panels, the Bell Labs astronomers explained the physics to the physicists.

Bell Labs had built the antenna in 1960 to receive coast-to-coast signals bouncing off the Echo communications satellite, a highly reflective balloon 100 feet in diameter. When the Echo mission ended, the antenna was used on the Telstar satellite. When that mission ended, Penzias and Wilson appropriated the antenna to study radio waves from the fringes of our Milky Way galaxy. The measurements would have to be much more sensitive than they were for Echo, so Penzias had built a cold load, an instrument that emitted a specific signal that he and Wilson could compare with measurements from the antenna to make sure it wasn't detecting any excess noise. And the cold load worked, just not in the way they'd hoped. Aside from the unavoidable rattling of electrons in the atmosphere and within the instrument itself, Penzias and Wilson were left with a persistent, inexplicable hiss.

For much of the past year they had been trying to determine the source of the noise. They pointed the antenna at New York City, less than fifty miles away. The radio static was negligible. They pointed the antenna at every other location on the horizon. The same. They checked the signal from the stars to see whether it differed from what they'd already factored into their calculations. Nope. The

phases of the Moon? Temperature changes in the atmosphere over the course of a year? No and no. That spring they had turned their attention back to the antenna itself. They put tape over the aluminum rivets in the antenna—nothing—and took apart the throat of the horn and put it back together again—nothing—and even scraped away the droppings from a pair of pigeons that had taken up residence within the horn. (They caught the pigeons and mailed them to the Bell Labs site in Whippany, New Jersey, more than forty miles away; the birds turned out to be homing pigeons and were back in the horn within days.) Still nothing—nothing but the noise.

The five scientists repaired to a conference room on Crawford Hill, and now the physicists explained the astronomy to the astronomers. Dicke started writing on a blackboard. If the Big Bang interpretation of the history of the universe was correct, Dicke said, then the cosmos emerged in an unfathomably condensed, obscenely hot explosion of energy. Everything that would ever be in the universe was there then, rushing outward on a shock wave of space itself, and continuing to rush outward until it evolved into the universe we see today. And as the universe expanded, it cooled. One member of the Princeton collaboration—Jim Peebles, the colleague who wasn't present—had calculated what that initial level of energy would have been, and then he had calculated what the current level of energy, after billions of years of expansion and cooling, should be. That remnant energy—assuming it existed; assuming the Big Bang theory was right—would be measurable. And now, apparently, Penzias and Wilson *had* measured it. Their antenna was picking up an echo, all right but this time the source wasn't a radio broadcast from the West Coast. It was the birth of the universe.

Penzias and Wilson listened politely. Dicke himself didn't entirely believe what he was saying—not yet. He and the two other Princeton physicists satisfied themselves that Penzias and Wilson had run a clean experiment, then drove back to Princeton and told Peebles what they had learned. Peebles didn't entirely believe what he was hearing, either. He was cautious; but then, he was always cautious. The four collaborators agreed that scientific results require corroboration, a second opinion—in this case, their own. They would finish constructing their antenna on the roof of Princeton's Guyot Hall and see if it got the same reading as the Bell Labs antenna. Even if it did, they knew they would *still* have to proceed with caution. It's not often, after all, that you get to discover a new vision of the universe.

The American writer Flannery O'Connor once said that every story has "a beginning, a middle, and an end, though not necessarily in that order." By the 1960s, scientists wanting to tell the story of the universe—cosmologists, by definition—could proceed under the assumption that they were in possession of the middle of the narrative. They had the latest version of one of civilization's most enduring characters, the universe—in this case, an expanding one. Now they could ask themselves: How did Our Hero get here?

The capacity for narrative is, as far as we know, unique to our species, because our species is, as far as we know, the only one that possesses self-consciousness. We see ourselves. Not only do we exist, but we think about our existence. We envision ourselves occupying a context—or, in storytelling terms, a setting: a place and a time. To see yourself as existing in a specific place and at a particular time is to suggest that you have existed and that you will exist in other places and at other times. You know you were born. You wonder what happens when you die.

But it's not just you that you wonder about. You take a walk and look at the stars, and because you know you are taking a walk and looking at the stars, you understand that you are joining a story already in progress. You ask yourself how it all got here. The answer you invent might involve light and dark, water and fire, semen and egg, gods or God, turtles, trees, trout. And when you have fashioned a sufficiently satisfying answer, you ask yourself, naturally, where it all—and you with it—will end. Bang? Whimper? Heaven? Nothing?

These questions might seem to lie outside the realm of physics, and before 1965 most scientists considered cosmology to be mostly that: metaphysics. Cosmology was where old astronomers went to die. It was more philosophy than physics, more speculation than investigation. The fourth member of the Princeton team—the one who didn't make the trip to Bell Labs—would have included himself in the category of cosmology skeptic.

Phillip James Edwin Peebles—Jim to everyone—was all angles.

Tall and trim, he explained himself to the world through his elbows and knees. He would throw his arms wide, as if to embrace every possibility, then wrap them around his legs, as if to consolidate energy and focus—mannerisms not inconsistent with a man of conflicting sensibilities, which was how Jim Peebles saw himself. Politically he called himself a "bleeding-heart liberal," yet scientifically he identified himself as "very conservative," even "reactionary." He had learned from his mentor, Bob Dicke, that a theory can be as speculative as you like, but if it doesn't lead to an experiment in the near future, why bother? On one occasion (before he knew better), Peebles had mentioned that he might try to reconcile the two great physics theories of the twentieth century, general relativity and quantum mechanics. "Go find your Nobel Prize," Dicke answered, "and then come back and do some real physics."

Cosmology, to Peebles, was not real physics. It was a reversion to how scientists did science in the two millennia before there were scientists and science as we know them. Ancient astronomers called their method "saving the appearances"; modern scientists might call it "doing the best you could under impossible circumstances." When Plato challenged his students, in the fourth century B.C. to describe the motions of the celestial bodies through geometry, he didn't expect the answers on paper to represent what was actually happening in the heavens. That knowledge was unknowable because it was unattainable; you couldn't go into the sky and examine it for yourself. What Plato wanted instead was an *approximation* of the knowledge. He wanted his students to try to find the math to match not the facts but the appearances.

One student, Eudoxus, arrived at an answer that, in one form or another, would survive for two thousand years. For mathematical purposes he imagined the heavens as a series of nesting, concentric transparent spheres. Some of these spheres carried the heavenly bodies. Others interacted with those spheres to retard or accelerate their motions, in order to account for the appearance that the heavenly bodies all slow down or speed up throughout their orbits. Eudoxus assigned the Sun and the Moon three spheres each. To each of the five planets (Mercury, Venus, Mars, Saturn, Jupiter) he assigned an extra sphere to accommodate the appearance that they sometimes briefly reverse their motions against the backdrop of stars, moving west to east from night to night rather than east to west.* And then he added a sphere for the realm of the stars. In the end his system consisted of twenty-seven spheres.

Another student of Plato's, Aristotle, amended this system. He assumed the spheres were not just mathematical constructs but physical realities; to accommodate the mechanics of an interlocking system, he added counterturning spheres. His total: fifty-six. Around A.D. 150, Ptolemy of Alexandria assumed the task of compiling the existing astronomical wisdom and simplifying it, and he succeeded. His night sky was overrun with only forty spheres. The math still didn't match the appearances exactly, but close enough was good enough—as good as it was ever going to get.

Today, the 1543 publication of *De revolutionibus orbium coelestium* ("On the Revolutions of the Heavenly Spheres"), by the Polish astronomer Nicolaus Copernicus, is synonymous with the invention of a new universe: the Copernican Revolution. It has become a symbol of defiance against the Church's teachings. But it was the Church itself that had invited Copernicus to come up with a new math for the motions in the heavens, and it had done so for a sensible reason: The appearances once again needed saving.

Over the centuries the slight inconsistencies in the Ptolemaic version—the areas where the math

departed from the motions—had led to a gradual drift in the calendar, until seasons diverged from their traditional dates by weeks. Copernicus's work allowed the Church to reform the calendar in 1582 incorporating his math while dispensing with the notion of a Sun-centered universe. Like the ancients, Copernicus wasn't proposing a new universe, either physically or philosophically. Instead, he was formulating a new way to "save the appearances" of the existing universe. The true motions of that universe, however, were out of reach, had always been out of reach, and would always be out of reach.

And then, they weren't. In 1609, the Italian mathematician Galileo Galilei found new information about the universe at his fingertips—literally, thanks to the invention of a primitive telescope. *Look*, he said, leading the elders of Venice up the steps of the Campanile in the Piazza San Marco in August 1609 to demonstrate the benefit of fitting a tube with lenses: seeing farther. *Look*, he said barely six months later, in his pamphlet *Sidereus Nuncius* ("Starry Messenger"), heralding a new lesson: Seeing farther means seeing not just more of the same—a fleet of rival merchants or the sails of an enemy navy—but seeing more, period. That autumn, Galileo had trained his tube of longseeing on the night sky and had begun a lengthy program of discovering celestial objects that no other person had ever seen: mountains on the Moon, hundreds of stars, spots on the Sun, satellites of Jupiter, the phases of Venus. The invention of the telescope—the first instrument in history to extend one of the human senses—changed not only how far we could see into space, or how well. It changed our knowledge of what was out there. It changed the appearances.

Here was evidence that corroborated the central tenets of Copernicus's math—that Earth was a planet, and that it and all the other planets orbited the Sun. But just as important, here was *evidence*—the tool of the scientific method. Seeing farther didn't have to mean seeing more. The night sky might not have held more objects than met the naked eye. And we still couldn't go into the sky and see for ourselves how its motions worked. But we could examine the heavens closely enough to find not only the appearances but the facts.* And facts needed not saving but explaining.

In 1687 the English mathematician Isaac Newton provided two of those explanations in *Philosophic Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"). He reasoned that if Earth is a planet, then the formulae that apply in the terrestrial realm must apply in the celestial as well. Building on the mathematical work of Johannes Kepler and the observations of Galileo and his successors in astronomy, he concluded that the motions of the heavens require not dozens of spheres but a single law: gravitation. In 1705 his friend and sponsor Edmond Halley applied Newton's law to past observations of comets that had appeared in 1531, 1607, and 1682 to make the claim that they were one comet and that it* would return in 1758, long after his own death. It did. No longer would the math have to accommodate the motions of the heavens. Now the heavens had to accommodate the math. Take Newton's law of universal gravitation, apply it to the increasingly precise observations you could make through a telescope, and you had a universe that was orderly and predictable and, on the whole, unchanging—a cosmos that ran, as the most common metaphor went, like clockwork.

In the more than three and a half centuries between Galileo's climb up the Campanile and the phone call from Crawford Hill, the catalogue of the universe's contents seemed to grow with every improvement of the telescope: more moons around planets; more planets around the Sun; more stars. By the early twentieth century, astronomers had determined that all the stars we see at night, whether with our naked eyes or through telescopes, are part of one vast collection of stars, numbering in the tens of billions, that we long ago named the Milky Way because it seems to spill across the night sky. Did other vast collections of stars, each numbering in the tens of billions, exist beyond the Milky Way? A simple extrapolation from the earlier pattern of discovery raised the possibility. And astronomers even had a candidate, a class of celestial objects that might qualify as "island universes" all their own.

In 1781, the French astronomer Charles Messier had published a catalogue of 103 celestial smudges—~~blurry objects that he feared would distract astronomers looking for comets.~~ Astronomers could see that several of those 103 smudges were bunches of stars. As for the others, they remained mysteries, even as the quality of telescopes improved. Were these nebulous objects clouds of gas in the process of coalescing into yet more stars within our system? Or were the nebulae vast collections of tens of billions of stars separate from but equal in magnitude to our own vast collection? The astronomy community split on the question, and in 1920 two prominent astronomers conducted a so-called Great Debate at the National Museum of Natural History in Washington, D.C., to present the pros and cons of each argument.

Three years later, the American astronomer Edwin Hubble did what debate alone couldn't do: resolve the question through empirical evidence. On October 4, 1923, using the largest telescope in the world—the new 100-inch* on Mount Wilson, in the hills outside Pasadena—he took a photograph of the Great Andromeda Nebula, or M31 in the Messier catalogue. He thought he noted a "nova," or new star, so he returned to M31 the following night and took another photograph of the same spiral arm. When he got back to his office, he began comparing the new plates with other photographs of the nebula on a number of different dates and found that the nova was actually a variable, a kind of star that, as its name suggests, varies: It pulsates, brightening and dimming with regularity. More important, it was a Cepheid variable, the kind that brightens and dims at regular time intervals. That pattern, Hubble knew, could resolve the debate.

In 1908, the Harvard astronomer Henrietta Swan Leavitt had discovered a proportional relationship between the pulsation period of a Cepheid variable and its absolute brightness: the longer the period, the brighter the variable. Astronomers could then take that measure of luminosity and match it with another quantifiable relationship, the one between luminosity and distance: A source of light that's twice as distant as another source of light with the same luminosity appears to be one-fourth as bright; a source of light three times as distant appears to be one-ninth as bright; a source of light four times as distant would be one-sixteenth as bright; and so on. If you know how often a variable pulsates, then you know how bright it is relative to other variables; if you know how bright it is relative to other variables, then you know how distant it is relative to other variables. When Hubble compared the pulsation period of the Cepheid variable he'd found in M31 with the pulsation periods of other Cepheid variables, he concluded that the variable was at sufficient distance that it (and therefore its host nebula, M31) lay beyond the "island universe"—or, as we would now have to think of it, *our* island universe.

Hubble went back to H335H, the photographic plate he made on October 5, and in posterity-radiant red he marked the variable star with an arrow, along with a celebratory "VAR!" He declared M31 an island universe all its own, and in so doing, he added to the cosmic canon one more *more*: galaxies.

Newton's clockwork universe began to come apart in 1929. After his "VAR!" breakthrough, Hubble had continued to investigate "island universes," especially some inexplicable measurements of them that astronomers had been making for more than a decade. In 1912 the American Vesto Slipher began examining the nebulae with a spectrograph, an instrument that registers the wavelengths from a source of light. Much like the sound waves of a train whistle as the train approaches or departs from a station, light waves are compressed or stretched—they bunch up or elongate—depending on whether the source of the light is moving toward you or away from you. The *speed* of the light waves doesn't change; it remains 186,282 miles (or 299,792 kilometers) per second. What changes is the *length* of the waves. And because the length of the light waves determines the colors that our eyes perceive, the color of the source of light also seems to change. If the source of light is moving toward you, the waves bunch up, and the spectrometer will show a shift toward the blue end of the spectrum. If the

source of light is moving away from you, the waves relax, and the spectrometer will show a shift toward the red end of the spectrum. And as the velocity of the source of light as it moves toward you or away from you increases, so does the blueshift or redshift—the greater the velocity, the greater the shift. Slipher and other astronomers had shown that some of the nebulae were registering significant redshifts, suggesting that they were moving away from us at great velocities. Now that Hubble knew these nebulae were galaxies, he wondered what these motions might mean. He found out when he compared the velocities of eighteen of these nebulae with their distances: The two measurements seemed to be directly proportional to each other—the farther the galaxy was, the faster it appeared to be receding. In other words, the universe might seem to be expanding.

Suddenly the universe had a story to tell. Instead of a still life, it was a movie. And like any narrative, the story of the universe now had not only a middle—the present, swarming with galaxies fleeing one another—but the suggestion of a beginning.

Precisely—*precisely*—at this point, at least from the perspective of a philosophically cautious sort like Jim Peebles, cosmology departed from science, passing from math to myth. You couldn't know how the universe began because the evidence was out of reach, just as it had been for Aristotle, Ptolemy, and Copernicus. They couldn't go across space to retrieve it; you couldn't go into the past. All you could do was observe the present phenomena—these redshifted galaxies—and try to find the math to accommodate their motions. All you could do was try to save the appearances, if that was your idea of science.

Hubble himself, as an observer, hoarding evidence and leaving the theorizing to the theorists, preferred to remain agnostic as to whether the universe really was expanding or whether another interpretation might explain the apparent correlation. But some theorists couldn't resist the challenge of rewinding the film. The Belgian priest Georges Lemaître, a physicist and astronomer, imagined the expansion unreeling in reverse, the size of the universe shrinking, smaller and smaller, the galaxies rushing back together, faster and faster, until the infalling matter would reach a state that he called the "primeval atom" and that other astronomers would come to call a "singularity": an abyss of infinite density and incalculable mass and energy.

But words such as "infinite" and "incalculable" aren't of much use to mathematicians, physicists or other scientists. "The unrestricted repeatability of all experiments is the fundamental axiom of physical science," Hermann Bondi and Thomas Gold, two Austrian expatriates living in Britain, wrote in the first line of a paper they submitted in July 1948 that outlined an alternative to Lemaître's theory. The following month, their friend Fred Hoyle, a British astronomer, submitted his own variation on this theme. Rather than a big bang—the term Hoyle applied, during a BBC radio broadcast in March 1949, to the idea of a universe expanding* from, as he wrote in his paper, "causes unknown to science"—they postulated a steady state. Through "continuous creation of matter," Hoyle wrote, "it might be possible to obtain an expanding universe in which the proper density of matter remained constant." Over the course of cosmic history, the creation of even infinitesimal amounts of matter could become cumulatively significant. Such a universe wouldn't have a beginning or an end; it would just *be*.

For many astronomers, however, "continuous creation" was no more appealing than a "singularity." Both the Big Bang and Steady State theories seemed to require a leap of faith, and faith not being part of the scientific method, there they let the matter rest.

But what if there *was* evidence for one theory or the other?

Bob Dicke asked Jim Peebles this question one sweltering evening in 1964. Peebles had arrived at Princeton as a graduate student six years earlier. At the University of Manitoba he had been the top student in physics, winning academic honor after honor. At Princeton he was shocked at how much

physics he didn't know. He spent his first year trying to catch up, and then one day some friends invited him to a get-together that Dicke ran most Friday evenings in the attic of Palmer Physical Laboratory. The Gravity Group was an informal gathering of a dozen or so undergraduates, graduates, postdocs, and senior faculty—"Dicke birds," they called themselves. Peebles went, and then he went back. He began to understand that here, in a sometimes-stifling setting at an inconvenient hour, he could get an education: eating pizza, drinking beer, and trying to figure out how to rehabilitate general relativity.

General relativity had been around for nearly half a century; Einstein had arrived at the equations in late 1915. Whereas Newton imagined gravity as *a force* that acts *across* space, Einstein's equations cast gravity as a *property* that belongs *to* space. In Newton's physics, space was passive, a vessel for a mysterious force between masses. In Einstein's physics, space was active, collaborating with matter to produce what we perceive as gravity's effects. The Princeton physicist John Archibald Wheeler offered possibly the pithiest description of this co-dependence: "Matter tells space how to curve. Space tells matter how to move." Einstein in effect reinvented physics. Yet by 1940 Dicke could ask a professor of his at the University of Rochester why the graduate physics curriculum didn't include general relativity, and the answer was that the two had nothing to do with each other.

Einstein might have agreed. A sound theory needs to make at least one specific prediction. General relativity made two. One involved an infamous problem of Einstein's era. The orbit of Mercury seemed to be slightly wrong, at least according to Newton's laws. The observable difference between Newton's and Einstein's versions of gravity were negligible—except in circumstances involving the most extreme cases, such as a tiny planet traveling close to a gargantuan star. Newton's equations predicted one path for Mercury's orbit. Observations of Mercury revealed another path. And Einstein's equations accounted precisely for the difference.

Another prediction involved the effect of gravity on light. A total eclipse of the Sun would allow astronomers to compare the apparent position of stars near the rim of the darkened Sun with their position if the Sun weren't there. According to general relativity, the background starlight should appear to "bend" by a certain amount as it skirted the great gravitational grip of the Sun. (Actually, in Einstein's theory it's space itself that bends, and light just goes along for the ride.) In 1919 the British astronomer Arthur Eddington organized two expeditions to observe the position of the stars during an eclipse on May 29, one expedition to Principe, an island off the west coast of Africa, the other to Sobral, a city in northeastern Brazil. The announcement in November 1919 that the results of the experiments seemed to validate the theory made both Einstein and general relativity international sensations.*

Yet Einstein himself downplayed the theory's power to predict "tiny observable effects"—its influence on physics. Instead, he preferred to emphasize "the simplicity of its foundation and its consistency"—its mathematical beauty. Mathematicians tended to agree, as did physicists such as Dicke's professor at the University of Rochester. General relativity's known effects in the universe—an anomaly in the orbit of a planet, the deflection of starlight—were obscure in the extreme; its unknown effects on the history of the universe—cosmology—were speculative in the extreme. Even so, Einstein also acknowledged that if the theory made a prediction that observations contradicted, then, as would be the case with any theory under the standards of the scientific method, science should amend or abandon it.

By the time Dicke joined the Princeton faculty in the 1940s, after the war, Einstein was as much a spectral presence in life as his theory was in experimental physics. Sometimes a seemingly homeless man would shuffle into a faculty party, and the younger folks in the crowd would need a moment to recognize the shock of hair and the basset-hound eyes. During the 1954–55 academic year, Dicke took a sabbatical leave at Harvard, and he found himself returning to thoughts of general relativity. As a

scientist who was equally at ease designing equipment and constructing theories, Dicke realized he could do what previous generations couldn't have done with their existing technology. When he returned to Princeton, he resolved to put Einstein to the test.

His experiments over the coming years would involve placing occulting disks in front of the Sun to determine its precise shape, which affects its gravitational influence on the objects in the solar system, including Mercury; bouncing lasers off the Moon and using the round-trip time to measure its distance from Earth, which would indicate if its orbit was varying from Einstein's math in the same way that Mercury's orbit varied from Newton's math; and using the chemical composition of stars to trace their age and evolution, which in turn would be important for tracing the age and evolution of the universe, which in turn would involve an attempt to detect the relic radiation from the primeval atomic cosmic fireball, Big Bang, or whatever you wanted to call it. Dicke wondered if a theory of the universe could avoid not only a Big Bang singularity but the Steady State's spontaneous creation of matter, and he proposed a compromise of sorts: an oscillating universe.

Such a universe would bounce from expansion to contraction to expansion throughout eternity, without ever reaching absolute collapse or, between collapses, eternal diffusion. During the expansion phase of such a universe, galaxies would exhibit redshifts consistent with what astronomers were already observing. Eventually the expansion would slow down under the influence of gravity, then reverse itself. During the contraction phase, galaxies would exhibit blueshifts as they gravitated back together. Eventually the contraction would reach a state of such compression that it would explode outward again, before the laws of physics broke down. Dicke's oscillating universe would therefore neither emerge from nor return to the dreaded singularity, though the earliest period of its current expansion would resemble a Big Bang. During one particularly muggy meeting of the Gravity Group, Dicke ended a discussion of that theory by turning to two of his Dicke birds, Peter Roll and David Todd Wilkinson, and saying, "Why don't you look into making a measurement?" They could build a radio antenna to detect the radiation from the most recent Big Bang. Then he turned to a twenty-nine-year-old postdoc and said, "Why don't you go think about the theoretical consequences?"

Jim Peebles had already forced himself to learn cosmology. As a graduate student at Princeton he had been required to pass the Physics Department's general examinations, and when he looked at previous years' exams, he saw that they reliably included questions on general relativity and cosmology. So he studied the standard texts of the day, *Classical Theory of Fields*, by Lev Landau and Evgeny Lifschitz, from 1951, and *Relativity, Thermodynamics, and Cosmology*, by Richard C. Tolman from 1934. Both books came with a whiff of formaldehyde; they presented cosmology in the embalmed terms of long-settled truths. The more Peebles educated himself about cosmology, the less he trusted it. General relativity itself excited him; he was a loyal and enthusiastic member of the Gravity Group. What appalled him were the assumptions that theorists had forcibly yoked to general relativity in order to create their cosmologies.

The trouble, Peebles saw, started with Einstein. In 1917, two years after arriving at the theory of general relativity, Einstein published a paper exploring its "cosmological considerations." What might general relativity say about the shape of the universe? In order to simplify the math, Einstein had made an assumption: The distribution of matter in the universe was homogeneous—that is, uniform on a large scale. It would look the same no matter where you were in it. In calculating the implications of Einstein's theory, Georges Lemaitre and, independently, the Russian mathematician Aleksandr Friedman had adopted the same assumption and added one more, that the universe is isotropic—uniform in every direction. It would look the same no matter which way you looked. Then the Steady State theory went the Big Bang one assumption better: The universe is homogeneous and isotropic not only throughout space but over time. It would look the same in every direction no matter where you were in it and no matter when.

Peebles tried to be fair; he attended a lecture on the Steady State theory. But he came away thinking, "They just made this up!" To Peebles, a homogeneous universe, whether in space or time or both, was not a serious model. Tolman's book came right out and said as much: Theorists assumed homogeneity "primarily in order to secure a definite and relatively simple mathematical model, rather than to secure a correspondence to known reality." This approach reminded Peebles of those oversimplified problems on exams: *Calculate the acceleration of a frictionless elephant on an inclined plane.*

"Boy, this is silly," Peebles thought. Why, he asked himself, would anyone imagine the universe to be, of all the things that a universe could be, *simple*? Yes, scientists preferred to follow the principle of Ockham's razor, dating back to the fourteenth-century Franciscan friar William of Ockham: Try the simplest assumptions first and add complications only as necessary. So Einstein's invocation of a homogeneous universe had a certain logic to it, a legacy behind it—but not enough to be the basis of a science that made predictions that led to observations.

Yet when Dicke approached him about figuring out the temperature of the most recent Big Bang in an oscillating universe, Peebles immediately accepted the challenge. First, the request came from Bob Dicke, and you had to trust his hunches. Besides, Peebles shared not only his mentor's enthusiasm for exploring general relativity but Dicke's reservations about cosmology. Only a year earlier, in 1961 in an article on cosmology and relativity for the *American Journal of Physics*, Dicke had written: "Having its roots in philosophic speculations, cosmology evolved gradually into a physical science, but a science with so little observational basis that philosophical considerations still play a crucial if not dominant role."

What appealed to Peebles was the chance to shore up that "observational basis"—the experimental implications. It was the possibility that his calculations might lead to an actual measurement, one that Roll and Wilkinson would make, using the radio antenna that Dicke had assigned them to build. They would be doing cosmology the scientific way: The appearances were going to have to accommodate Jim Peebles's math.

The first hint that radio waves might offer a new way of seeing the universe dated to the 1930s—again, through an accidental detection at Bell Labs. In 1932 an engineer who had been trying to rid transatlantic radiotelephone transmissions of mystery static figured out that the noise was coming from the stars of the Milky Way. The news made the front page of the *New York Times* but then receded into obscurity. Even astronomers regarded the discovery as a novelty. Not until after World War II did the use of radio waves to study astronomy become widespread.

Radio astronomy turned out to be part of a larger dawning of awareness among astronomers that the range of the electromagnetic spectrum beyond the narrow optical band might contain useful information. The wavelengths to which human eyes have evolved to be sensitive range from 1/700,000th of a centimeter (red) to 1/400,000th of a centimeter (violet). To either side of that narrow window of sight, the lengths of electromagnetic waves increase and decrease by a factor of about one quadrillion, or 1,000,000,000,000,000. The Princeton experiment would concentrate on some of the longest waves because they would have the lowest energy—the kind that radiation that had been cooling from very nearly the beginning of time would have reached by now.

Peebles began by using the present constitution of the universe to work backward toward the primordial conditions. The present universe is about three-quarters hydrogen, the lightest element; its atomic number is 1, meaning that it has one proton. In order for such an abundance of hydrogen to have survived to the present day, the initial conditions must have contained an intense background of radiation, because only an extraordinarily hot environment could have fried atomic nuclei fast enough to keep all those single protons from fusing with other subatomic particles to form helium and heavier elements. As the universe expanded—as its volume grew—its temperature fell. Extrapolate from the

current percentage of hydrogen how intense the initial radiation must have been, calculate how much the volume of the universe has expanded since then, and you have the temperature to which the initial radiation would by now have cooled.

A radio antenna, however, doesn't measure temperature, at least not directly. The temperature of an object determines the motions of its electrons—the higher the temperature, the greater the motions. The motions of the electrons in turn are what produce radio noise—the greater the motions, the more intense the noise. The intensity of the noise therefore tells you how much the electrons are moving, which tells you the temperature of the object—or what engineers call the "equivalent temperature" of the radio noise. In a box with opaque walls, the only source of radio noise will be the motions of the electrons in the walls. If you place a radio receiver in a box that happens to be the universe, then the intensity of the static will tell you the equivalent temperature of the walls of the universe: the relic radiation.

In 1964 Peebles got to work predicting the current temperature of the relic radiation—the equivalent temperature of the static that an antenna would need to detect. Meanwhile, his colleagues Roll and Wilkinson began work on the antenna—technically, a Dicke radiometer, invented by Dicke to refine radar sensitivity during the war, while he was working at the Radiation Laboratory at the Massachusetts Institute of Technology. In early 1965, Peebles received an invitation from Johns Hopkins University's Applied Physical Laboratory to give a talk, and he asked Wilkinson if he could mention the radiometer in public.

"No problem," Wilkinson said. "No one could catch up with us now."

What happened next happened fast. Peebles delivered his talk on February 19. In the audience was a good friend of Peebles's from graduate school (and a former Dicke bird), Kenneth Turner, a radio astronomer at the Carnegie Institution's Department of Terrestrial Magnetism (DTM), in Washington, D.C. The experiment made an impression on Turner, and a day or two later he mentioned the colloquium to another radio astronomer at DTM, Bernard Burke. Another day or two later, during a communal lunch, Burke got a phone call from a Bell Labs radio astronomer he'd met in December on a plane ride to an American Astronomical Society meeting in Montreal. Burke went into the kitchen's anteroom to take the call. After a brief discussion, Burke made small talk. "How is that crazy experiment of yours coming?" he said.

On the flight to Montreal, Arno Penzias had described for Burke the work he and Bob Wilson were doing on Crawford Hill. He had told Burke that they hoped to study the radio waves from the stars not in the big bulge at the center of the Milky Way, where most astronomers had been looking, but in the other direction, at the fringe of the Milky Way halo. But now, he said to Burke on the phone, they'd run into a problem even before they could begin their observations.

"We have something we don't understand," Penzias said. He explained that he and Wilson couldn't get rid of an excess noise corresponding to a temperature near, but not quite, absolute zero. When Penzias had finished describing their efforts and their frustration, Burke said, "You should probably call Bob Dicke at Princeton."

The Big Bang was a creation myth, but by 1965 it was a creation myth with a difference: It came with a prediction. By the time Penzias placed his call to Dicke, Peebles had arrived at a temperature of approximately 10° Celsius above absolute zero, which is more commonly referred to as 10 Kelvin.* Penzias and Wilson had found a measurement of 3.5 K (plus or minus 1 K) in their antenna. Because Peebles's calculations were rudimentary and Penzias and Wilson's detection was serendipitous, the approximation of theory and observation was hardly definitive. Yet it was also too close to dismiss as a coincidence.

At the very least it was worth recording for posterity. After the Crawford Hill meeting and a reciprocal meeting at Princeton, the two sets of collaborators agreed that they would each write a

paper, to appear side by side in the *Astrophysical Journal*. The Princeton foursome would go first, discussing the possible cosmological implications of the detection. Then the Bell Labs duo would confine their discussion to the detection itself, so as not to align their measurement too closely with a wild interpretation that, as Wilson said, it "might outlive."

On May 21, 1965, even before their papers appeared, the *New York Times* broke the story: "Signals Imply a 'Big Bang' Universe." (The reporter had been in contact with the *Astrophysical Journal* about another upcoming paper when he heard about these two papers.) The prominence of the coverage—placement on the front page; an accompanying photograph of the Bell Labs telescope—impressed some of the scientists in the two collaborations with the possible impact of their (possible) discovery. Peebles, though, didn't need the news media to tell him they were onto something big. All he had to do was look at Dicke. Dicke could be humorous and lighthearted, but not about physics. In recent weeks, though, he had clearly been enjoying himself in a different way. After talking to Dicke one longtime Princeton astronomer reported back to his peers that Bob Dicke was "bubbling with excitement."

A subsequent search of the literature turned up other predictions and at least one previous detection. In 1948, the physicist George Gamow had written a *Nature* paper that predicted the existence of "the most ancient archeological document pertaining to the history of the universe." He was wrong on the details but right on the general principle: The early universe had to be extremely hot to avoid combining all the hydrogen into heavier elements. That same year, the physicists (and sometime collaborators of Gamow's) Ralph Alpher and Robert Herman published their calculation that "the temperature in the universe" should now be around 5 K, but astronomers at the time assured them that such a detection would be impossible with current technology. (In retrospect Wilson felt that they probably could have performed it with World War II-era technology, as long as they had properly connected the antenna to the cold load.) In a 1961 article in the *Bell System Technical Journal*, a Crawford Hill engineer wrote that the Echo antenna was picking up an excess of 3 K; but that reading fell within the margin of error, and the discrepancy wasn't going to make a difference for his purposes anyway, so he ignored it. In 1964, Steady State champion Hoyle, working with fellow British astronomer Roger J. Tayler, investigated the oscillating-universe scenario and performed calculations similar to those of Alpher and Herman. Also in 1964, even as Penzias and Wilson were directing their antenna to every point on the horizon in a futile effort to find the source of their excess noise, two Russian scientists published a paper pointing out that a detection of the cosmic background radiation was currently possible—and that the ideal instrument was a certain horn antenna on a hilltop in Holmdel Township, New Jersey.

Jim Peebles had a high metabolism; he could eat whatever he wanted and not worry about gaining weight. This inherent restlessness extended to his intellectual life. He loved identifying the next big problem, solving it, seeing where it led, identifying *that* big problem, solving it, seeing where it led: a bend-in-the-knees, wind-in-the-face rush into the future. (He was an expert downhill skier.) Even the description of his intellectual restlessness that he once gave to a journalist was restless: "a random walk, no, an undirected walk, or rather a locally directed walk: as you take each step you decide where the next one is going to go." The library part of the scholarly process, however, the burrowing into the stacks, the boning up on the literature—maybe it didn't bore him, exactly, but it didn't engage him either. In any case, he hadn't done his homework.

His initial paper on the temperature of the universe—Dicke had forwarded a preprint to Penzias after the phone call about the Bell Labs detection—had repeatedly bounced back from the *Physical Review* referee because it was duplicating earlier calculations by Alpher, Herman, Gamow, and others. Peebles finally withdrew the paper in June 1965. He managed to rectify some of those oversights in the paper on the cosmic microwave background he wrote with Dicke, Roll, and Wilkinson. Even that

paper, however, referred only to Gamow's work on the primordial creation of elements, not to his work predicting the temperature of the cosmic background. Gamow sent an angry note to Penzias, listing citations of his early work and concluding, "Thus, you see, the world did not start with almighty Dicke."

Still, the obscurity in which these documents languished was a reflection of the indifference many scientists felt toward cosmology and general relativity. No longer. By December 1965, Roll and Wilkinson had mounted their antenna on the roof of Guyot Hall and gotten the same reading as Penzias and Wilson. Within months two more experiments (one by Penzias and Wilson) had found what a sound scientific prediction demands: a duplication of results—in this case, a detection of what was already being called "the 3-K radiation."

You could feel the shift, if you were an astronomer or physicist. Both the Steady State and Big Bang interpretations had relied not just on math and observation but on speculation. They were modern counterparts to Copernicus's attempt to save the appearances; they were theories in need of evidence. And just as Galileo, with the aid of the telescope, had detected the celestial phenomena that decided between an Earth-centered and a Sun-centered cosmos, forcing us to reconceive the universe so radio astronomers, with the aid of a new kind of telescope, were now detecting the evidence that decided between the Steady State and Big Bang cosmologies, necessitating a further reconception of the universe.

Seeing beyond the optical part of the electromagnetic spectrum didn't have to mean seeing more. The sky might not have harbored more information than meets the eye, even one aided by an optical telescope. The introduction of radio astronomy could have left the Newtonian conception of the universe intact. But seeing beyond the optical did mean seeing more phenomena and having to accommodate new kinds of information. This new universe would still run like clockwork; the laws that had arisen through Galileo's observations and Newton's computations would still presumably apply. But now, so would Hubble's and Einstein's, and in their universe the motions of the heavens weren't cyclical so much as linear; their cosmos corresponded not so much to a pocket watch, its hands and gears grinding and turning but always returning to the same positions, as to a calendar, its fanning pages preserving the past, recording the present, and promising the future.

Maybe, Peebles thought, making theories of the universe wasn't so silly after all. Not that the always-cautious Peebles now embraced the Big Bang theory. But the uniformity of the microwave background that he had predicted and that Penzias and Wilson had detected would certainly correspond to a universe that looked the same on the largest scales no matter where you were in it. Einstein had posited an elephant on an incline, and that's what the universe turned out to be: homogeneous.

"Which is an amazing thing," Peebles thought. "But there it is: The universe is simple."

2. What's Out There

WHAT THE UNIVERSE could be, or should be, didn't much concern her. She wasn't a theorist. She was an astronomer—an observer. The universe was what it was. And what it was, everywhere you looked, was in motion.

Well, she wasn't an astronomer *yet*. She'd never actually observed, except as a child, using a telescope that her father had helped her build out of a lens she'd ordered through the mail and a cardboard linoleum tube she'd gotten free from a store in downtown Washington, D.C. And that telescope didn't even work properly; she couldn't take pictures of the stars with it, because it couldn't track their motions—or, more accurately, their apparent motions, since it's the turning of the Earth that gives stars the illusion of arcing across the night sky.

She should have known that the camera wouldn't work. The motions of the stars were part of what got her interested in astronomy. Her second-floor bedroom window—the one right above her bed—faced north, and around the age of ten she noticed that the stars appeared to be slowly circling a point in the northern sky, and that over the seasons the stars themselves changed. Ever since, she found that she would rather track the motions of the night sky than sleep. She memorized the paths of meteors, then registered them in a notebook in the morning. Later, in high school, whenever she had to write a research paper the topic she chose was invariably something to do with astronomy—reflecting telescopes (the kind with mirrors) or refracting telescopes (the kind with lenses). At a certain point in the evening her mother might call up the stairs, "Vera, don't spend the whole night with your head out the window!" But she did, and her parents didn't seem to mind, not really.

Hers was, in a way, a Newtonian view of the universe: matter in motion; predictable patterns; celestial objects (and the Earth was one, too, if you thought about it) that, for all their peregrinations, invariably wound up back where they started. But Vera Cooper was born in 1928, three years after Edwin Hubble announced that our Milky Way galaxy was hardly singular, and one year before he presented evidence that the galaxies seemed to be receding from one another—the farther apart, the faster. The only universe she'd known was full of galaxies, and those galaxies were in motion.

And so, as a graduate student at Cornell, when she had to think about a topic for her master's thesis, she tried to update the old clockwork view of the cosmos for the new expanding universe. She reasoned that since the Earth rotated on its axis, and the solar system rotated, and the galaxy rotated, then maybe the universe had an axis too. Maybe the whole universe rotated.

The premise seemed reasonable. Her husband, Robert Rubin, a doctoral candidate in physics at Cornell, had shown her a brief, speculative article by George Gamow in the journal *Nature*, "Rotating Universe?" Then she heard that Kurt Godel, at Princeton, was working on a theory of a rotating universe.

Her approach also seemed reasonable. She gathered data on the 108 galaxies for which astronomers had managed to measure a redshift. Then she separated out the motions that were due to the expansion of the universe—what astronomers call recessional motions. Did the motions that remained—the peculiar motions—exhibit a pattern? She plotted them on a sphere and thought they did. In December 1950, at the age of twenty-two, still half a year shy of getting her master's degree, Vera Cooper Rubin presented her thesis at an American Astronomical Society meeting in Haverford, Pennsylvania.

Rubin had never suffered from a lack of confidence. When an admissions officer at Swarthmore College told her that because astronomy was her profession of choice and painting was one of her favorite hobbies, she might want to consider a career as a painter of astronomical scenes, she laughed and applied to Vassar. When she got a scholarship to Vassar and a high school teacher told her, "As

long as you stay away from science, you should do okay," she shrugged and pursued a BA in astronomy (with a heavy load of philosophy of science on the side). When a Cornell professor told her that because she had a one-month-old son he would have to take her place at the Haverford AAS meeting and present her paper in his own name, she said, "Oh, I can go," and, nursing newborn and all, she went.

The response from the AAS crowd when she concluded her presentation was nearly unanimous: The premise was odd, the data weak, the conclusion unconvincing. The criticism continued until the astronomer Martin Schwarzschild kindly signaled an end to the discussion by rising and saying, in a high-pitched voice, "This is a very interesting thing to have attempted." The moderator called a coffee break, and Rubin left the meeting.

She herself hadn't thought her paper was extraordinary; it was a master's thesis, after all. Still, she thought that as master's theses went, it was fine. She had taken a pile of numbers and handled them in the most careful fashion she knew, and she thought the result was worth reporting. She thought that she'd given a good talk, and that she'd given it as well as she could. She reminded herself that she had never been to an AAS meeting before, and that she hadn't even met many professional astronomers. Maybe this was just how astronomers behaved. She decided she would file these criticisms in the same category as the comments from the admissions officer and her teachers. The next day her hometown paper the *Washington Post* ran an article under the headline "Young Mother Figures Center of Creation by Star Motions." So she could console herself that real astronomers would at least know who she was (or, because of a typo, who "Vera Hubin" was).

Still, the experience did teach Rubin an important lesson: She was such a novice that she didn't know how far out of the mainstream her work was. She didn't know that Gamow was nearly alone among astronomers, and Godel among theorists, in finding the question of a rotating universe worthy of serious consideration. Gamow had admitted, in the *Nature* paper, that the idea of a rotational universe was "at first sight fantastic"—which, at first sight, it was. But what if you didn't trust first sight? First sight—the evidence of the senses, unaided by technology—tells you that the Earth is stationary, that the Sun revolves around the Earth, that Jupiter is moonless and Saturn ringless and the stars motionless, and that the stars are as far as there is. The point Gamow was trying to make was that astronomers needed to go beyond first sight, because now they had a new scale of the universe to consider.

Saying that all the billions of stars we see are part of our galaxy and that billions of galaxies lie beyond our own doesn't do justice to the scale of the universe. Just as our eyes didn't need to evolve to see radio waves in order for us to survive, maybe our minds didn't need to evolve to understand the numbers that astronomers were now trying to incorporate into their thinking. Like cultures that count "One, two, three, more," we tend to regard the scale of the universe—to the extent that we regard it at all—as "Earth, planets, Sun, far."

Consider: How long would it take you to count to a million at the "one Mississippi" rate of one second per number? Eleven days—or, to be exact, 11 days, 13 hours, 46 minutes, and 40 seconds. How long would it take you to count to a billion at the same rate? A billion is a thousand million—that is, million one thousand times over. So you would have to count a million Mississippis—eleven days of counting—a thousand times. That's 31 years, 8% months. To reach a trillion, you'd have to count to a billion a thousand times—31 years a thousand times, or 31,000 years. A light-year—the distance light travels in a year—is about six trillion miles. To count to six trillion, you would need six sets of 31,000 years, or 186,000 years.

Earlier generations of astronomers had to learn to adjust their thinking to accommodate successive discoveries about new scales of the universe: that the Sun is 93 million miles distant; that the nearest star after the Sun is 4.3 light-years, or 25 trillion miles, away (that's 186,000 years of

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