13 Things That Don't Make Sense

The Most Intriguing Scientific Mysteries of Our Time

Michael Brooks

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Extract

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The most exciting phrase to hear in science, the one that heralds the most discoveries, is not "Eureka!," but "That's funny . . ."

—ISAAC ASIMOV

CONTENTS

PROLOGUE

I am standing in the magnificent lobby of the Hotel Metropole in Brussels, watching three Nobel laureates struggle with the elevator.

It's certainly not an easy elevator to deal with; it's an open mesh cage, with a winch system that looks like something Isambard Kingdom Brunel might have built. When I first got into it three days ago, I felt like I was traveling back in time. But at least I got it to work.

Embarrassed for the scientists, I look away for a moment and distract myself with the grandeur of my surroundings. The Metropole was built at the end of the nineteenth century and is almost ridiculously ornate. The walls are paneled with vast slabs of marble, the ceilings decorated in subtle but beautiful gold and sage green geometric patterns. The glittering crystal chandeliers radiate a warmth that makes me want to curl up and go to sleep beneath their light. In fact, there are glowing, comforting lights everywhere. Outside, in the Place de Brouckère, the wind is blowing a bitter cold across the city; faced with the bleak December beyond those revolving doors, I feel like I could stand here forever.

The Nobel laureates are still struggling. No one else seems to have noticed their plight, and I'm wondering whether to walk across the lobby and offer help. When I had my long fight with the door, I discovered there's something about the shutter mechanism that defies logic—when you think it must be locked, it isn't; it needs a final pull. But it occurs to me that people who have attached Nobel Academy pins to their lapels ought to be able to work that out for themselves.

I like to think of scientists as being on top of things, able to explain the world we live in, masters of their universe. But maybe that's just a comforting delusion. When I can tear myself away from the farce playing out in the elevator, I will be getting into a cab and leaving behind perhaps the most fascinating conference I have ever attended. Not because there was new scientific insight—quite the contrary. It was the fact that there was no insight, seemingly no way forward for these scientists, that made the discussions so interesting. In science, being completely and utterly stuck can be a good thing; it often means a revolution is coming.

The discussion at the conference was focused on string theory, the attempt to tie quantum theory together with Einstein's theory of relativity. The two are incompatible; we need to rework them to describe the universe properly, and string theory may be our best bet. Or maybe not. I have spent the last three days listening to some of today's greatest minds discuss how we might combine relativity and quantum theory. And their conclusion was that, more than three decades after the birth of string theory, we still don't really know where to start.

This was a Solvay physics conference, a meeting with the richest of histories. At the first Solvay conference in 1911—the world's first physics conference—the delegates debated what was to be made of the newly discovered phenomenon of radioactivity. Here in this hotel Marie Curie, Hendrik Lorentz, and the young Albert Einstein debated how it was that radioactive materials could apparently defy the laws of conservation of energy and momentum. Radioactivity was an anomaly; it didn't make sense. The problem was eventually solved by the birth of quantum theory. At the 1927 Solvay conference, though, the strange nature of quantum theory caused its own problems, provoking Einstein and Niels Bohr, Lorentz and Erwin Schrödinger, Ernest Rutherford and John von Neumann to sit discussing these new laws of physics with the same degree of confusion as they had shown toward radioactivity.

It was an extraordinary moment in the history of science. Quantum theory encapsulated the novel idea that some things in nature are entirely random, happen entirely without cause. This made no sense to Einstein or Bohr, and the pair spent their time outside the formal discussions sparring over what it all meant. They had entirely different philosophical approaches to dealing with that mystery, however. To Bohr, it meant some things might be beyond the scope of science. To Einstein, it meant something was wrong with the theory; it was here in this hotel that Einstein made his famous remark that "God does not play dice." Bohr's reaction faces up to scientists' biggest frustration: that they don't get to set the rules. "Einstein," he said, "stop telling God what to do."

Neither man lived to see a satisfactory solution to the enigma—it remains unsolved, in fact. But if some delegates at the twenty-third Solvay conference are to be believed, it seems Bohr might have been right about there being limits to science. Half of the string theorists present, some of the greatest minds in the world, are now convinced that we can never fully comprehend the universe. The other seekers after a "theory of everything" think there must be some explanation available to us. But they have no idea where to find it. What has led to this extraordinary situation? Yet another anomaly.

This one was discovered in 1997. Analysis of the light from a distant supernova led astronomers to a startling conclusion: that the universe is expanding, and that this expansion is getting faster and faster all the time. The revelation has stunned cosmologists; no one knows why this should be so. All they can say is that some mysterious "dark energy" is blowing up the universe.

This anomaly, an apparently simple observation, has brought string theory to its knees. It cuts away at everything its proponents thought they had achieved. Put simply, they can't explain it—and many of them feel they should stop trying. There is a straightforward answer staring us in the face, they say: our universe must be one of many universes, each with different characteristics. To try to find reasons why those characteristics are as they are in our universe, they argue, is a waste of time.

But it is not. There is something inspiring about this—and any—anomaly. When Thomas Kuhn wrote *The Structure of Scientific Revolutions* in the early 1960s, he wanted to examine the history of science for clues to the nature of discovery. The clues led him to invent the term—now a cliché—*paradigm shift.* Scientists work with one set of ideas about how the world is. Everything they do, be it experimental or theoretical work, is informed by, and framed within, that set of ideas. There will be some evidence that doesn't fit, however. At first, that evidence will be ignored or sabotaged. Eventually, though, the anomalies will pile up so high they simply cannot be ignored or sabotaged any longer. Then comes crisis.

Crisis, Kuhn said, is soon followed by the paradigm shift in which everyone gains a radically new way of looking at the world. Thus were conceived ideas like relativity, quantum theory, and the theory of plate tectonics.

The dark energy situation is another such crisis. You can see it as depressing, a hint that science has hit a brick wall. But, equally, you can see it as exciting and inspiring. Something has now got to give, and the breakthrough could come from anywhere at any time. What is even more exciting is that it is not the only anomaly of our time—not by a long way.

It is not even the only one in cosmology. Another cosmic problem, dark matter, was first spotted in the 1930s. Following Kuhn's template almost exactly, it was ignored for nearly forty years. Vera Rubin, an astronomer at Washington, D.C.'s Carnegie Institution, was the one to nail it down and make people deal with it. In the early 1970s, she showed that the shape, size, and spin of galaxies means either there is something wrong with gravity or there's much more matter out there in space than we can see. No one wants to mess with Newton's laws governing gravity, but neither do we know what this dark matter might be.

It's sometimes comforting to imagine that science is mastering the universe, but the facts tell a different story. Put together, dark matter and dark energy make up 96 percent of the universe. Just two anomalous scientific results have told us that we can see only a tiny fraction of what we call the cosmos. The good news is that cosmologists are now, perhaps, emerging from Kuhn's crisis stage and are in the process of reinventing our universe—or they will be once they manage to work out where the paradigm shift should lead.

Other, equally stirring anomalies—revolutions-in-waiting, perhaps—await our attention closer to home too. There is the placebo effect: carefully planned, rigorously controlled experiments repeatedly show that the mind can affect the body's biochemistry in ways that banish pain and produce startling medical effects. Except that, like dark matter, no one is quite sure that the placebo effect really exists. Cold fusion experiments, where nuclear reactions inside metal atoms safely release more energy than they consume, have also survived nearly two decades of skepticism, and the U.S. Department of Energy recently declared that the laboratory evidence is strong enough to merit funding of a new round of experimental research. The thing is, cold fusion goes against all the received wisdom in physics; there is no good explanation for why it should work—or even strong evidence that it does. But it is still worth investigating: the hints that we do have suggest that it could expose a new, deeper theory of physics that could have an enormous impact on many aspects of science. Then there is the "intelligent" signal from outer space that has defied explanation for thirty years; the enigma of our sense of free will despite all scientific evidence to the contrary; the spacecraft that are being pushed off course by an unknown force; the trouble we have explaining the origin of both sex and death using our best biological theories . . . the list goes on.

The philosopher Karl Popper once said, rather cruelly perhaps, that "science may be described as the art of systematic oversimplification." Though that is an oversimplification in itself, it is clear that science still has plenty to be humble about. But here is the point that is often missed by scientists eager to look as if nothing is beyond their abilities. Dark energy has been described as the most embarrassing problem in physics. But it is not; it is surely the greatest opportunity in physics—it gives us reason to examine our oversimplifications and correct them, bringing us to a new state of knowledge. The future of science depends on identifying the things that don't make sense; our attempts to explain anomalies are exactly what drives science forward.

In the 1500s, a set of celestial anomalies led the astronomer Nicolaus Copernicus to the realization that the Earth goes around the Sun—not the other way around. In the 1770s, the chemists Antoine Lavoisier and Joseph Priestley inferred the existence of oxygen through experimental results that defied all the theories of the time. Through several decades, plenty of people noticed the strange jigsaw-piece similarity between the east coast of South America and the west coast of Africa, but it wasn't until 1915 that someone pointed out it could be more than a coincidence. Alfred Wegener's insightful observation led to our theory of plate tectonics and continental drift; it is an observation that, at a stroke, did away with the "stamp-collecting" nature of geologic science and gave it a unifying theory that opened up billions of years of Earth's history for inspection. Charles Darwin performed a similar feat for biology with his theory of evolution by natural selection; the days of remarking on the wide variety of life on Earth without being able to tie them all together were suddenly over. It is not just an issue of experiments and observations either; there are intellectual anomalies. The incompatibility of two theories, for example, led Albert Einstein to devise relativity, a revolutionary theory that has forever changed our view of space, time, and the vast reaches of the universe.

Einstein didn't win his Nobel Prize for relativity. It was another anomaly—the strange nature of heat radiation—that brought him science's ultimate accolade. Observations of heat had led Max Planck to suggest that radiation could be considered as existing in lumps, or quanta. For Planck, this quantum theory was little more than a neat mathematical trick, but Einstein used it to show it was much more. Inspired by Planck's work, Einstein proved that light was quantized—and that experiments could reveal each quantum packet of energy. It was this discovery, that the stuff of the universe was built from blocks, that won him the 1922 Nobel Prize for Physics.

Not that a Nobel Prize for Physics is the answer to everything—my view across the Metropole's lobby makes that abundantly clear. Why can't these three men, three of the brightest minds of their generation, see the obvious solution? I can't help wondering if Einstein struggled with that elevator; if he did, by now even he, shaking his fist at the Almighty, would have called out for help.

Admitting that you're stuck doesn't come easy to scientists; they have lost the habit of recognizing it as the first step on a new and exciting path. But once you've done it, and enrolled your colleagues in helping resolve the sticky issue rather than proudly having them ignore it, you can continue with your journey. In science, being stuck can be a sign that you are about to make a great leap forward. The things that don't make sense are, in some ways, the only things that matter.

1

THE MISSING UNIVERSE

We can only account for 4 percent of the cosmos

The Indian tribes around the sleepy Arizona city of Flagstaff have an interesting take on the human struggle for peace and harmony. According to their traditions, the difficulties and confusions of life have their roots in the arrangement of the stars in the heavens—or rather the lack of it. Those jewels in the sky were meant to help us find a tranquil, contented existence, but when First Woman was using the stars to write the moral laws into the blackness, Coyote ran out of patience and flung them out of her bowl, spattering them across the skies. From Coyote's primal impatience came the mess of constellations in the heavens and the chaos of human existence.

The astronomers who spend their nights gazing at the skies over Flagstaff may find some comfort in this tale. On top of the hill above the city sits a telescope whose observations of the heavens, of the mess of stars and the way they move, have led us into a deep confusion. At the beginning of the twentieth century, starlight passing through the Clark telescope at Flagstaff's Lowell Observatory began a chain of observations that led us to one of the strangest discoveries in science: that most of the universe is missing.

If the future of science depends on identifying the things that don't make sense, the cosmos has a lot to offer. We long to know what the universe is made of, how it really works: in other words, its constituent particles and the forces that guide their interactions. This is the essence of the "final theory" that physicists dream of: a pithy summation of the cosmos and its rules of engagement. Sometimes newspaper, magazine, and TV reports give the impression that we're almost there. But we're not. It is going to be hard to find that final theory until we have dealt with the fact that the majority of the particles and forces it is supposed to describe are entirely unknown to science. We are privileged enough to be living in the golden age of cosmology; we know an enormous amount about how the cosmos came to be, how it evolved into its current state, and yet we don't actually know what most of it *is.* Almost all of the universe is missing: 96 percent, to put a number on it.

The stars we see at the edges of distant galaxies seem to be moving under the guidance of invisible hands that hold the stars in place and stop them from flying off into empty space. According to our best calculations, the substance of those invisible guiding hands—known to scientists as *dark matter*—is nearly a quarter of the total amount of mass in the cosmos. Dark matter is just a name, though. We don't have a clue what it is.

And then there is the *dark energy*. When Albert Einstein showed that mass and energy were like two sides of the same coin, that one could be converted into the other using the recipe $E = mc^2$, he unwittingly laid the foundations for what is now widely regarded as the most embarrassing problem in physics. Dark energy is scientists' name for the ghostly essence that is making the fabric of the universe expand ever faster, creating ever more empty space between galaxies. Use Einstein's equation for converting energy to mass, and you'll discover that dark energy is actually 70 percent of the mass (after Einstein, we should really call it mass-energy) in the cosmos. No one knows where this energy comes from, what it is, whether it will keep on accelerating the universe's expansion forever, or whether it will run out of steam eventually. When it comes to the major constituents of the universe, it seems no one knows anything much. The familiar world of atoms—the stuff that makes us up—accounts for only a tiny fraction of the mass and energy in the universe. The rest is a puzzle that has yet to be solved.

HOW did we get here? Via one man's obsession with life on Mars. In 1894 Percival Lowell, a wealthy Massachusetts industrialist, had become fixated on the idea that there was an alien civilization on the red planet. Despite merciless mocking from many astronomers of the time, Lowell decided to search for irrefutable astronomical evidence in support of his conviction. He sent a scout to various locations around the United States; in the end, it was decided that the clear Arizona skies above Flagstaff were perfect for the task. After a couple of years of observing with small telescopes, Lowell bought a huge (for the time) 24-inch refractor from a Boston manufacturer and had it shipped to Flagstaff along the Santa Fe railroad.

Thus began the era of big astronomy. The Clark telescope cost Lowell twenty thousand dollars and is housed in a magnificent pine-clad dome on top of Mars Hill, a steep, switchbacked track named in honor of Lowell's great obsession. The telescope has an assured place in history: in the 1960s the Apollo astronauts used it to get their first proper look at their lunar landing sites. And decades earlier an earnest and reserved young man called Vesto Melvin Slipher used it to kick-start modern cosmology.

Slipher was born an Indiana farm boy in 1875. He came to Flagstaff as Percival Lowell's assistant in 1901, just after receiving his degree in mechanics and astronomy. Lowell took Slipher on for a short, fixed term; he employed Slipher reluctantly, as a grudging favor to one of his old professors. It didn't work out quite as Lowell planned, however. Slipher left fifty-three years later when he retired from the position of observatory director.

Though sympathetic to his boss's obsession, Slipher was not terribly interested in the hunt for Martian civilization. He was more captivated by the way that inanimate balls of gas and dust—the stars and planets—moved through the universe. One of the biggest puzzles facing astronomers of the time was the enigma of the spiral nebulae. These faint glows in the night sky were thought by some to be vast aggregations of stars—"Island Universes," as the philosopher Immanuel Kant had described them. Others believed them to be simply distant planetary systems. It is almost ironic that, in resolving this question, Slipher's research led us to worry about what we can't see, rather than what we can.

IN 1917, when Albert Einstein was putting the finishing touches to his description of how the universe behaves, he needed to know one experimental fact to pull it all together. The question he asked of the world's astronomers was this: Is the universe expanding, contracting, or holding steady?

Einstein's equations described how the shape of space-time (the dimensions of space and time that together make the fabric of the universe) would develop depending on the mass and energy held within it. Originally, the equations made the universe either expand or contract under the influence of gravity. If the universe was holding steady, he would have to put something else in there: an *antigravity* term that could push where gravity exerted a pull. He wasn't keen to do so; while it made sense for mass and energy to exert a gravitational pull, there was no obvious reason why any antigravity should exist.

Unfortunately for Einstein, there was consensus among astronomers of the time that the universe was holding steady. So, with a heavy heart, he added in the antigravity term to stop his universe expanding or contracting. It was known as the *cosmological constant* (because it affected things over cosmological distances, but not on the everyday scale of phenomena within our solar system), and it was introduced with profuse apologies. This constant, Einstein said, was "not justified by our actual knowledge of gravitation." It was only there to make the equations fit with the data. What a shame, then, that nobody had been paying attention to Vesto Slipher's results.

Slipher had been using the Clark telescope to measure whether the nebulae were moving relative to Earth. For this he used a spectrograph, an instrument that splits the light from telescopes into its constituent colors. Looking at the light from the spiral nebulae, Slipher realized that the various colors in the light would change depending on whether a nebula was moving toward or away from Earth. Color is our way of interpreting the frequency of—that is, the number of waves per second in—radiation. When we see a rainbow, what we see is radiation of varying frequencies. The violet light is a relatively high-frequency radiation, the red is a lower frequency; everything else is somewhere in between.

Add motion to that, though, and you have what is known as the *Doppler effect*: the frequency of the radiation seems to change, just as the frequency (or pitch) of an ambulance siren seems to change as it speeds past us on the street. If a rainbow was moving toward you very fast, all the colors would be shifted toward the blue end of the spectrum; the number of waves reaching you every second would get a boost from the motion of the rainbow's approach. This is called a blueshift. If the rainbow was racing away from you, the number of incoming waves per second would be reduced and the frequency of radiation would shift downward toward the red end of the spectrum: a redshift.

It is the same for light coming from distant nebulae. If a nebula were moving toward Slipher's telescope, its light would be blueshifted. Nebulae that were speeding away from Earth would be redshifted. The magnitude of the frequency change gives the speed.

By 1912 Slipher had completed four spectrographs. Three were redshifted, and one—Andromeda—was blueshifted. In the next two years Slipher measured the motions of twelve more galaxies. All but one of these was redshifted. It was a stunning set of results, so stunning, in fact, that when he presented them at the August 1914 meeting of the American Astronomical Society, he received a standing ovation.

Slipher is one of the unsung heroes of astronomy. According to his National Academy of Sciences biography, he "probably made more fundamental discoveries than any other twentieth century observational astronomer." Yet, for all his contributions, he got little more than recognition on two maps: one of the moon, and one of Mars. Out there, beyond the sky, two craters bear his name.

The reason for this scant recognition is that Slipher had a habit of not really communicating his discoveries. Sometimes he would write a terse paper disseminating his findings; at other times he would put them in letters to other astronomers. According to his biography, Slipher was a "reserved, reticent, cautious man who shunned the public eye and rarely even attended astronomical meetings." The appearance in August 1914 was an anomaly, it seems. But it was one that set an English astronomer called Edwin Powell Hubble on the path to fame.

The Cambridge University cosmologist Stephen Hawking makes a wry observation in his book *The Universe in a Nutshell.* Comparing the chronology of Slipher's and Hubble's careers, and noting how Hubble is credited with the discovery, in 1929, that the universe is expanding, Hawking makes a pointed reference to the first time Slipher publicly discussed his results. When the audience stood to applaud Slipher's discoveries at that American Astronomical Society meeting of August 1914, Hawking notes, "Hubble heard the presentation."

By 1917, when Einstein was petitioning astronomers for their view of the universe, Slipher's spectrographic observations had shown that, of twenty-five nebulae, twenty-one were hurtling away from Earth, with just four getting closer. They were all moving at startling speeds—on average, at more than 2 million kilometers per hour. It was a shock because most of the stars in the sky were doing no such thing; at the time, the Milky Way was thought to be the whole universe, and the stars were almost static relative to Earth. Slipher changed that, blowing our universe apart. The nebulae, he suggested, are "stellar systems seen at great distances." Slipher had quietly discovered that space was dotted with myriad galaxies that were heading off into the distance.

When these velocity measurements were published in the *Proceedings of the American Philosophical Society*, no one made much of them, and Slipher certainly wouldn't be so vulgar as to seek attention for his work. Hubble, though, had obviously not forgotten about it. He asked Slipher for the data so as to include them in a book on relativity, and, in 1922, Slipher sent him a table of nebular velocities. By 1929 Hubble had pulled Slipher's observations together with those of a few other astronomers (and his own) and come to a remarkable conclusion.

If you take the galaxies moving away from Earth, and plot their speeds against their distance from Earth, you find that the farther away a galaxy is, the faster it is moving. If one receding galaxy is twice as far from Earth as another, it will be moving twice as fast. If it is three times more distant, its speed is three times greater. To Hubble, there was only one possible explanation. The galaxies were like paper dots stuck onto a balloon; blow it up, and the dots don't grow, but they do move apart. The very space in between the galaxies was growing. Hubble had discovered that the universe is expanding.

It was a heady time. With this expansion, the idea of a big bang, first suggested in the 1920s, bubbled to the surface of cosmology. If the universe was expanding, it must once have been smaller and denser; astronomers began to wonder if this was the state in which the cosmos had begun. Vesto Slipher's work had led to the first evidence of our ultimate origins. The same evidence would eventually bring us the revelation that most of our universe is a mystery.

TO understand how we know a significant chunk of the cosmos is missing, tie a weight to a long piece of string. Let the string out, and swing the weight around in a circle. At the end of a long string, the weight moves pretty slowly—you can watch it without getting dizzy. Now pull the string in, so the weight is doing tiny orbits of your head. To keep it spinning around in the air, rather than falling down and strangling you, you have to keep it moving much faster—so fast you can hardly see it.

The same principle is at work in the motions of the planets. The Earth, in its position close to the Sun, moves much faster in its orbit than Neptune, which is farther out. The reason is simple: it's about balancing forces. The gravitational pull of the Sun is stronger at Earth's radial distance out from the Sun than at Neptune's. Something with Earth's mass has to be moving relatively fast to maintain its orbit. For Neptune to hold its orbit, with less pull from the distant Sun, it goes slower to keep in equilibrium. If it moved at the same speed as Earth, it would fly off and out of our solar system.

Any orbiting system ought to follow this rule: balancing a gravitational pull and the centrifugal forces means that, the farther something is from whatever is holding it in orbit, the slower it will move. And, in 1933, that is exactly what a Swiss astronomer called Fritz Zwicky didn't see.

As construction began on the Golden Gate Bridge and a forty-three-year-old Adolf Hitler was appointed chancellor of Germany, Zwicky noticed something odd about the Coma cluster of galaxies. Roughly speaking, stars emit a certain amount of light per kilo, so, looking at the amount of light coming out of the Coma cluster, Zwicky could estimate how much stuff it contained. Zwicky's problem was that the stars on the edges of the galaxies were moving far too fast to be constrained by the gravitational pull of that amount of material. According to his calculations, the only explanation was that there was about four hundred times more mass in the Coma cluster than could be accounted for by the cluster's visible matter.

It should have been enough to launch the dark matter hunt, but it wasn't—for the worst of scientific reasons. Comb the Internet for references to Zwicky, and you'll find *brilliant* next to *maverick*, *genius* next to *insufferable*. Like Slipher, he doesn't figure large in the astronomy textbooks, despite his many important discoveries. He was the first to see that galaxies form clusters. He coined the term *supernova*. He was certainly one of a kind. He built a ski ramp next to the Mount Wilson Observatory in the San Gabriel Mountains of California, for example; in the winter Zwicky would haul his skis to work so he could keep his ski-jumping skills honed. But it was his interpersonal skills that needed most attention. He was a prickly, difficult man, convinced of his own genius, and convinced that he never got the recognition he deserved. He had a tendency to refer to all his colleagues as "spherical bastards": bastards whichever way you looked at them. Small wonder, then, that his colleagues turned a blind eye to his discovery of the Coma cluster's missing mass.

But he was right. Something about the mass of galaxies just doesn't add up—unless, that is, the universe is heavily sprinkled with dark matter. In 1939, at the dedication of the McDonald Observatory in Texas, the Dutch astronomer Jan Oort added to the evidence. Oort gave a lecture in which he showed the distribution of the mass in a certain elliptical galaxy had to be very different from the distribution of the light. He published the data three years later, making this very point clear in the abstract. Again, in a classic Kuhnian response, no one reacted. This spectacular ability to ignore such anomalous results continued for decades until, for some reason, people finally listened to Vera Rubin.

Rubin, who is now in her late seventies, made her first big mark on cosmology at the age of twenty-two. The New Year's Eve, 1950, edition of the *Washington Post* reported on a talk she gave at the American Astronomical Society, hailing her achievements under the headline "Young Mother Figures Center of Creation by Star Motions." The accompanying piece described how Rubin's work was "so daring . . . that most astronomers think her theories are not yet possible." But her most daring work, the fight to get dark matter taken seriously, was still to come.

Not that she even took herself seriously to start with. The story, she says, is a lesson in how dumb a scientist can be. In 1962 Rubin was teaching at Georgetown University in Washington, D.C. Most of her students were from the U.S. Naval Observatory down the road, and they were very good astronomers, she recalls. Together they were able to map out the *rotation curve* of a galaxy. This is a graph that shows how the velocity of the stars changes as you move out from the center of the galaxy. As with that weighted string twirling around your head, the velocities should fall as you get farther out. For Rubin and her naval researchers, though, they didn't; once they got away from the center, the curve was flat. They presented the results in a series of three papers, and Rubin made nothing of it.

Three years later, in 1965, she took a job at the Carnegie Institution of Washington. After a year in the cutthroat business of looking for quasars, the most distant objects known, she wanted to do something a little less competitive, something she could make her own. She decided to look at the outside of galaxies because no one had studied them—everyone concentrated on the centers. Not only had Rubin completely forgotten about her work with the Naval Observatory students, she also didn't believe her own results as she was gathering them. She measured the speeds by looking at how the motion had changed the spectrum of light coming from a star. Rubin was gathering about four spectra each night, gradually going farther and farther out from the center of the galaxy. Even though she developed the spectra as she went along, and they all looked the same, the penny didn't drop.

"You always thought the next point would fall," she says. "And it just didn't."

Eventually, though, she got it. By 1970 Rubin had mapped out the rotation curve for Andromeda; the star velocities remained the same however far out she looked. With the velocities of the stars remaining high at the edge, centrifugal forces should be throwing Andromeda's outer stars off into deep space. By rights, Andromeda should be falling apart. Unless, that is, it is surrounded by a halo of dark matter.

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