Cosmos Incognito:
Vera Rubin Shines Light on Dark Matter

by

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Abstract

This thesis, a profile of astronomer Vera Rubin, highlights her scientific achievements, most notably the irrefutable evidence she gathered to persuade the astronomical community that galaxies spin at a faster speed than Newton's Universal Law of Gravitation allows. As a result of this finding, astronomers conceded that the universe must be filled with more material than they can see. Scientists call this mysterious substance dark matter.

This submission explains the scientific history of dark matter, its acceptance, and the current research being done to test its existence. It also mentions counter theories to the dark matter hypothesis and looks at Vera Rubin's current work and how this research will help astronomers better understand the construction of the cosmos and its evolution.

Thesis Supervisor: Marcia Bartusiak
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At First Peak

A flick of a switch and Vera Rubin disappears. The darkness of a telescope silo swallows her tiny frame. Moving by instinct, she takes a few steps, grabs the banister of a staircase, and climbs upward. Her footsteps echo throughout the pitch-black dome. At the top, Rubin reaches a door. Putting her key into the lock, she turns the knob and pushes. Nothing happens. Like a lineman, she lowers her center of gravity and throws her weight against the hinged hunk of metal, bumping it open with her hip.

A gust of wind knocks her in the face as she steps outside onto a rusted, iron catwalk. Finally she looks up toward the heavens. In all directions, stars speckle the southern Arizona sky. The seeing looks good, Rubin says as she traces her way around the outside of the dome to yet another door. Opening it, she looks in. For the first time that evening, Rubin can make out the silhouette of the monster cyclops she and fellow astronomer Deirdre Hunter are about to awaken.

Twilight beckons at Kitt Peak National Observatory, just west of Tucson. It's close to six p.m. Rising on the eastern horizon, are two "star cities," the galaxies NGC 801 and UGC 2885. They are too faint to see, but still Rubin pauses, as if searching the sky for them. She then turns and heads back to the telescope's control room. After removing her gloves and hat, Rubin smoothes her cropped, white hair. Her attention then shifts to Hunter, who is systematically pressing at two panels of large, square buttons. Faint rumbles begin. Outside, on the side of the dome, a 25-foot, metal garage door retracts on its hinges. Hunter next clicks "open mirror cover," giving the telescope's 84-inch-wide, silvered glass eye its first peek at the stars. Like a plane engine revving for takeoff, the telescope hums as it shifts into position. After taking time to focus and calibrate the instrument, Rubin and Hunter finally set the machine for its first half-hour exposure of the night.

To pass the time, Hunter settles into the chair in front of her personal laptop and switches on the Eyecam. In a few seconds, her computer makes a ringing sound and the face of a grinning youngster fills the screen. "Hi Rita," says Hunter. That makes Rubin turn, wave, and begin to sing "Happy Birthday" to the little girl who will be turning four the next day. The younger astronomer chats with her daughter for a few minutes, blows her a kiss, and then wishes the child a good night. Rita's image flickers out. With a flicker, a swirling ebony spiral, the galaxy NGC 801, appears.

By now, it's quarter to eight, and this vortex of stars sits a little higher above the horizon than it did when Rubin last checked the sky. It resides at a distance of 258 million light-years from Earth in the constellation Andromeda.

Beep.

Slowly, a new swirling image loads onto her monitor. Eager to calculate the width of NGC 801, Rubin leans in close to the screen. She pushes her round, shell-pink glasses up her nose and furrows her brow. The computer image's size is tricky to relate to the galaxy' s actual diameter, she says to Hunter, who then gives her a few calibration tips. A second later, Rubin picks up her pencil, scribbles down two number sets, and quickly flips to the back of her logbook where she keeps the data she's been collecting for more than twenty years.

"We are getting more distance than I got in 1980," she concludes.

In that year's June edition of the *Astrophysical Journal* Rubin had written that she and her colleagues would try to study the stars residing at the extreme fringes of galaxies.

Now, twenty-seven years later, the octogenarian astronomer has returned to Kitt Peak. She's determined to deliver on that promise and also push the limits of an observational practice she began decades ago.

Rubin measures how swiftly stars circulate around the heart of a galaxy. Most of the stars move at the same speed, even the ones sitting at a spiral's periphery. When she first observed this behavior, Rubin was startled. All astronomers were. The outer stars' swift speeds seemed to defy the laws of physics. Scientists once thought that stars would move around a galaxy just as the planets circle the sun; the closest objects would move the fastest while the ones farthest from the Sun's gravitational grip should travel much slower. Astronomers, based on the information they had, assumed that a spiral's stars acted the same way. But, much to their surprise, the constituent stars of a galaxy do not behave this way at all.

From this and others findings, nature demanded that astronomers develop an entirely new structure of the cosmos. It needed more matter to keep stars from flying off. This extra material, however, may not be composed of the same substance as us. Atoms, in fact, may turn out to be only a tiny fraction of the stuff in the universe. Something else entirely new could make up the majority, close to ninety percent. It is invisible and inscrutable, and that is why scientists call it dark matter. Exposed by Vera Rubin's observations, this cosmos incognito is one of the grandest enigmas in twenty-first century astronomy, a mystery yet to be solved.

An Uncertain Beginning

When scientists first wrote the phrase dark matter into the astronomical lexicon, Vera Rubin was in kindergarten. She was too young to know that across the country from her Philadelphia home a maverick astronomer at the California Institute of Technology was conjuring up the need for "dunkle Materie," as he first described it in a Swiss physics journal.

Just shy of Rubin's fifth birthday, in 1933, Fritz Zwicky was grappling to explain why eight galaxies he was studying were circulating within the Coma cluster way too fast. Upon examining the galaxies' speeds, the Caltech scientist reasoned that an invisible mass had to be exerting an immense tug on all of them, holding them in. Without this material's gravity, he surmised, the speedy galaxies would have been zipping out of the cluster altogether; instead, they all were sticking together comfortably in their little clan.

Zwicky's dark matter hypothesis went unheeded. Few astronomers at the time were ready to consider a universe made of a material not yet describable and irritatingly unseen. Similar discoveries of fast galaxies in the Virgo Cluster, and even fast-moving stars circulating in our nearest spiraling neighbor, the Andromeda galaxy, did nothing to bolster the idea that an invisible mass pervaded the universe. It was not a topic astronomers regularly discussed during the mid-to-late thirties. The hypothesis seemed too absurd.

Around this time, Rubin, her parents, and her older sister moved south to Washington D.C., where Rubin's father got a job at the Department of Agriculture after struggling to find work during the Depression. Home life for Rubin, however, gave no hint of difficulty. She remembers taking piano lessons, having her hair stand on end while learning of the effects of electricity at the University of Pennsylvania's Van de Graaff machine, and even building her own kaleidoscope using polished shards of glass as the interior reflectors. These seemingly random childhood activities honed Rubin's curiosity with nature, an intense inquisitiveness that would later drive her scientific career.

The stars mesmerized Rubin most. Night after night she would sit at her window watching the sky, memorizing where each meteor streaked across it. In the morning, she would draw a map tracing the meteors' paths. "I was interested in their motions," she recalls. So curious about these celestial objects, she traveled alone to downtown Washington. "I picked up this free cardboard tube that linoleum came in, and brought it home on the bus. I bought a two-inch lens from Edmunds, and I built a telescope." She was not yet twelve-years-old.

Anything Rubin needed to foster her fervent desire to understand nature, her father would help her get. He even took her to the D.C. Amateur Astronomer Club meetings, where she heard the ideas of such notable astronomers as Harlow Shapley and David Menzel. Not everyone was as supportive as her father. When she proudly showed her high school physics teacher her acceptance letter to Vassar College, he quickly retorted, "As long as you stay away from science, you should do all right." Stubbornly she ignored his advice, and in the fall of 1945, she packed her bags and headed for New York's Hudson Valley. She became the only member of her class to major in astronomy.

Almost instantly she connected with her mentor, Maude Makemson, the first real scientist with whom she had direct contact. The young astronomy student also had the opportunity to make herself at home with the school's small telescope, and having chosen to accelerate her program, was slated to graduate at the end of three years.

Prior to her final year, she fell in love with Robert Rubin, and by the fall of 1947 was engaged. Not yet twenty, she was looking forward to a summer wedding, and Rubin now found her relationship with her mentor a bit strained. "I probably wasn't serious enough for her," she recalls. "I think she thought I was going to go off and get married and that would be the end of astronomy."

It was not the end, but just the beginning. Rubin joined her husband at Cornell University, where he was working on his doctoral degree in physics. In turn, she decided to earn a master's degree in astronomy and took courses from such brilliant luminaries as Hans Bethe, Richard Feynman, and Phillip Morrison. Most influential was a young astronomer named Martha Carpenter, who was deep into galaxy dynamics. Though neither mentor nor student recognized it then, this research area inspired Rubin and would continue to do so throughout her professional career.

For her masters thesis, Rubin asked whether or not large groups of galaxies moved like other bodies in the universe. It seemed logical that if planets circled the sun and stars orbited around the disk of a galaxy, then galaxies might exhibit some motion around a shared, central point—a universal rotation. They would swing around that point like carousel horses on a merry-go-round. Few scientists in the late 1940s were willing to speculate that such large-scale movements existed; most assumed that galaxies were randomly strewn about the universe and just recede away from us as the universe expands ever outward.

Rubin, though, thought it dangerous to assume anything in science. From the astronomical catalogues, she gleaned all the information she could on a set of thirty-eight galaxies lying relatively close to the Milky Way. She plodded through her calculations of the objects' overall speeds and discerned that the galaxies did exhibit some extra, unexplained sideways motion. Given this surprising conclusion, her thesis advisor, William Shaw, thought the results should be discussed at the 1950 winter meeting of the American Astronomical Society, the most preeminent organization of professional astronomers in North America. Since she was not an AAS member and then expecting a child, Shaw kindly offered to give the presentation for Rubin—under his own name.

Proud of her research and too tenacious to hand it over to anyone else, she chose to attend the meeting and speak for herself, just three weeks after giving birth. Before her talk, one of about fifty given that year at the gathering, the chairs in the Haverford, Pennsylvania meeting hall filled gradually. When Rubin entered the room, she recognized not one of the men sitting, waiting, whispering to one another as the twenty-two-year-old approached the lectern. She confidently posed her question, presented her data, and concluded her speech. Everyone in the room scoffed at Rubin's conclusions (which were confirmed in part years later). Only one prominent physicist responded in a somewhat approving tone to her research question, but even he kindly pointed out that to conclude with certainty that groups of galaxies exhibited extra motions, she needed more data. Rubin never forgot this criticism.

Upon receiving their degrees, the Rubins relocated to Washington D.C. where Robert had secured a post-doctoral position at the Applied Physics Laboratory in Maryland. "Bob went off to work every day, and I stayed home with the baby," says Rubin. "It was tough. It was just too tough *not* doing astronomy."

Robert Rubin recognized his wife's frustration immediately. "She was very unhappy with the life she was leading," he says, and "it was clear that something would have to be done." He insisted Vera return to school to earn her doctoral degree. By a lucky coincidence, the famed physicist George Gamow, best known for his theories on the origins of the chemical elements, called Rubin around this time to discuss her thesis. The conclusions she presented at the AAS meeting seemed to support his latest ideas about the configuration of the cosmos, and he started a discussion of his hypotheses with her over the phone. "It sort of tied me in a little bit with what he was doing in cosmology," says Rubin.

A few weeks later, Gamow met with Rubin. The imaginative Russian galvanized her dream of earning a doctoral degree at Georgetown, the only university in D.C. to offer a Ph.D. program in astronomy, and though he was at nearby George Washington University, special arrangements were made for Gamow to serve as Rubin's dissertation advisor. Over the next two years, the two met periodically to talk about Rubin's research question—how galaxies were spaced within the universe. She wondered whether there was a pattern in the positions of galaxies and their clusters or whether the celestial bodies were randomly situated about the sky; in other words, was there evidence of larger cosmic structures beyond clusters of galaxies. This was a relatively novel idea in the early fifties. Only a few papers in the astronomy journals touted the existence of large-scale cosmic configurations such as galactic superclusters or supergalaxies. Hardly anyone dared to suggest that galaxies were anything but smoothly distributed throughout the cosmos.

For months, Rubin spent her nights crunching data, often waking at two in the morning and toiling until dawn when her husband and children (by then a son and daughter) rose for another day of work and play. Calculating the positions of 108 galaxies, operations that could now be done in a matter of minutes with a computer, eventually showed the objects were not spread evenly throughout the universe. Instead they were clumped together in massive chunks, like curdles in a glass of milk.

Not many took the claim seriously. Scientists, many who led the country's prominent astronomy programs, were more inclined to hold fast to the conservative conception of an unwrinkled universe. Barely anyone acknowledged the finding. Those who did charged Rubin's evidence was wanting, despite her meticulous calculations. The avant-garde conclusion earned Rubin her Ph.D. in 1954, but it would be another thirty years before it was confirmed. More important, though, Rubin absorbed some of Gamow's unconventional flair for posing pointed and creative research questions. Working with him moved her toward a path-breaking career.

Starting with Stars

Her Ph.D. in hand, Rubin began collaborating with local scientists, all who taught her valuable research techniques. Especially supportive was solar astronomer Charlotte Moore Sitterly, who helped the newly minted scientist analyze data from the sun and the moon that became part of a classified military project. Yet, despite becoming a professor at Georgetown and collaborating with area astronomers, Rubin still felt estranged from the research community, for she was doing only projects assigned to her rather than studying galaxies. And when Rubin's husband garnered a post-doctoral position at the University of Illinois in Urbana-Champaign, Vera found she was barely allowed to set foot on the university's male-dominated campus. Her ability to connect with leading astronomers and physicists became even more challenging.

In the sixties, however, everything changed.

During the summer of 1960, the Rubins, now with four children, moved back to D.C., and Vera soon obtained grant money to pursue a research question of her choosing—

to peg how our home galaxy, the spiraling Milky Way, rotated. At the time the knowledge that other galaxies existed was fairly new, about as old as Rubin herself. The first discovery of a spiral beyond our own was validated in 1924. Since then scientists have struggled to make sense of how billions of stars could come together and arrange themselves into galaxies. Rubin hoped her study would help astronomers learn more about the structure of the Milky Way and its evolution.

At her Georgetown university office, and quite often at her dining room table, Rubin and her students scoured the astronomical catalogues searching for information on all of the hottest (and hence brightest) stars that lie beyond the Sun and away from the center of our galaxy. They also analyzed published data on objects lying close to our spiral's interior. By recording the positions of these stars and how fast they move through the galaxy, the astronomers could crudely gauge how the stars circulated within the Milky Way. Plotting the velocity of the selected stars versus the distance the stars were from the galactic center allowed the Georgetown group to draw a graph, what astronomers call a galactic rotation curve. What Rubin and, in fact, every other scientist expected to see in this drawing was a line that first rose abruptly, but then plateaued softly and began to fall. With large amounts of matter concentrated in the galaxy's core, scientists expected that the stars there would move at high velocities. Stars farther out from the center of the Milky Way would orbit the galaxy more slowly, since, at the fringes, cosmic densities were assumed to be much lower. The mechanics of our galaxy, in other words, should follow the model of our solar system.

It was simple Newtonian mechanics. In the seventeenth century, Sir Isaac Newton established the mathematical way in which a planet and the Sun, or any two objects, attract each other. This gravitational force, he figured out, varies with distance. Halve the distance between two objects and the attraction between the two is increased by a factor of four; quadruple the distance and the force between the objects diminishes to a sixteenth. In essence, the gravitational attraction of two masses depends on the square of the distance between them.

According to legend, the Englishman's first clue to this principle came when he saw an apple fall toward Earth. From this mundane occurrence, he was able to work out that the force our planet has on everyday objects. Newton then realized he could extend his mathematical description beyond the Earth—to all the planets and the Sun.

The solar system is, in fact, a perfect test case of Newton's Universal Law of Gravitation. Perhaps, the best way to understand this force is to compare the attraction between the Sun and Mercury versus the Sun and Pluto. Pluto is about 100 times more distant from the Sun than Mercury. Because of this great difference, the Sun tugs at Mercury 10,000 times harder than it does at Pluto.

As the Sun pulls at the planets, they move. The speed at which Mercury and Pluto orbit the Sun corresponds to how much tug the star has on each body. Because the gravitational force between Mercury and the Sun is so great compared to the Pluto/Sun attraction, the innermost planet whips around the star at a velocity roughly ten times faster than the distant dwarf planet. When graphing the velocities of the planets versus their distance, astronomers see a curve that starts out very high in the left and then drops off precipitately as the distance between the Sun and a planet increases.

For centuries, scientists have tested Newton's mathematical explanation of gravitation. Again and again, the result turns out the same: if the distance between two bodies increases, the force grows weaker and the velocity of the orbiting object drops.

Astronomers have substantial evidence of this phenomenon from not only our solar system, but from all sorts of heavenly bodies. To assume that stars in a galaxy would behave just as the planets do seemed only logical.

"Actually, in the abstract of one of the papers, we said that did *not* occur," recalls Rubin. The rotation curve she and her students drew for the Milky Way was unexpectedly, well, flat. The velocity did not drop off. The farthest stars Rubin's team could find were circulating our galaxy as fast as those near its heart. This was 1962. "I seem to have forgotten that for the next ten or fifteen years," notes Rubin.

Astronomers paid little attention to the group's finding. It clearly did not hold Rubin's curiosity either, perhaps because she relied on others' data instead of gathering the evidence for herself. Not that she could have collected the data anyway. Gaining access to the nation's preeminent observatories was, at the time, a daunting task for women: all the scheduled time at the biggest telescopes in the 1960s was reserved for men—and men alone.

Fortunately two events granted Rubin access to the heavens. In 1963, her husband received a fellowship that took the family to the University of California in San Diego, and coincidentally, it was the same university where Geoffrey and Margaret Burbidge were doing their latest research. A few years previously, the husband and wife team had helped establish that most of the chemical elements that compose the Earth—and therefore us—are cooked up in the hearts of the biggest stars. Rubin, a devout reader of the astronomical journals, was familiar with this work, but was more interested in their latest research on galaxies and how fast the innermost stars in the bright, central bulges circulated in them. Though a bit anxious, Rubin approached the couple. In just one interview, she proved herself, and the Burbidges gladly welcomed her to their team.

Working beside Mrs. Burbidge, Rubin learned how to use a spectrograph to study distant galaxies. This instrument, by exploiting either a prism or a grating, separates light into its component wavelengths. We've all seen this phenomenon when sunlight enters one side of a triangular glass and a rainbow—what scientists call a spectrum—emerges from the other side. Blue colors have the shortest wavelengths. From the crest of one wave to the crest of the next, is about 475 nanometers. (One nanometer equals about 40 billionths of an inch.) As you move along the color spectrum, from blue to green to yellow to red, the wavelengths of the colors get progressively longer. About 650 nanometers separates two wave crests of red light.

When elements such as sodium are heated, they also give off colors. If scientists use a spectrograph to look at this light, they do not see a rainbow. Instead they see a series of brightly colored lines, a band of blue or a stripe of red. These are called spectral lines. Sodium, for instance, has a distinct yellow line. Each element emits a specific pattern, and its arrangement of color bands serves as its fingerprint. Similar to the way the patterns of our fingerprints distinguish us from each other, spectral lines allow scientists to differentiate one element from another.

Negatively charged ions, atoms with extra electrons, also emit specific light waves called emission lines. A prime example of this emission comes from what astronomers label an H-II region, an area in space composed almost entirely of hydrogen gas. The gas cocoons hot, young blue stars. In an H-II object's spectrum, the strongest emission line always appears as the same wavelength of red, distinguishing the object's identity. It is also why, when we see a color picture of one of these regions, the area takes on a vibrant magenta hue.

An object's spectrum, its chemical fingerprint, tells scientists what elements make it up. But the spectral lines can also reveal how fast the object is moving. That's because they shift in proportion to how fast and in what direction the object is traveling. It is, in essence, light's take on the Doppler effect. We experience this effect with sound. The pitch of a police car's siren will get higher and higher as it moves toward us. That's because the wavelength becomes shorter as the car approaches. But after the car passes, and moves farther away, the sound waves stretch out. We hear the pitch drop.

Light waves work the same way. If a star is moving toward Earth, its spectral lines all shift over toward the blue end of the spectrum. That's because the waves get compressed as they head straight for us. They are "blueshifted." If the object is moving away from us, the lines shift over into the red spectral range. The wavelengths get longer and hence are "redshifted." Measuring the amount of shift in the spectral lines tells astronomers how fast the celestial object is moving. Because a galaxy is so vast, scientists take several spectral readings across the length of the galactic disk, measuring how fast each region is spinning. They then consolidate these data points and draw out a galaxy's rotation curve.

Rubin, with Margaret Burbidge as her mentor, mastered this observing technique and then gleaned from Geoffrey Burbidge and Kevin Prendergast the mathematics she needed to analyze the curve and use it to calculate how massive the spirals were. "Oh she really got a kick out of studying galaxies this way," recalls Mr. Burbidge, and says that in eight or nine months time, she became quite comfortable using the procedure and writing up the astronomers' findings for publication. Most satisfying for Rubin was accompanying Mrs. Burbidge to the McDonald Observatory in Texas. There she finally had her first taste of being a "real" astronomer, recognizing that she was no longer an outsider. "Margaret

Burbidge was studying galaxies. She was married, and she had a child," says Rubin. It was a life she dreamed of living. She saw it was possible and that she could indeed have it all.

Once her husband's fellowship ended, Rubin and her family headed back east. She returned to Georgetown with a portfolio bursting with published papers and her mind set on raising her children, observing, and getting back to the Milky Way's rotation curve. Lucky for her, the new Kitt Peak National Observatory had recently opened its facilities to *all* the nation's astronomers, not merely a chosen few. The no-women rule was reversed.

Rubin set out for Tucson and soon extended her measurements of the Milky Way's rotation far beyond what she had scraped together using astronomical catalogues alone. By the mid-1960s, her curve extended about five times farther than it had in the early part of that decade, and for the first time, the astronomer officially observed that the farthest stars in our spiral were indeed speeding around its edges at a clip roughly equal to the stars lying closer to the galactic core. The rotation curve, despite the added distance, remained flat.

Newton's laws seemed somehow suspended, just as they had been for Zwicky and other astronomers. But this time people took notice. Rubin's results caught the attention of some preeminent scientists from around the country, including the Mount Wilson astronomer Allan Sandage. He immediately sent her an application to compete for telescope time at the noted California observatory. Prominent on the form was the warning, "Due to limited facilities, it is not possible to accept applications from women," but for Rubin, Sandage had penciled in the word "usually." Soon granted time, she became the first women legally allowed to use the Mt. Wilson 48-inch telescope. Margaret Burbidge had observed there years before, but only as her husband's off-the-books "assistant."

Around this time, Rubin got wind of observations being done by astronomer Bernard Burke, who worked at the DTM, or Department of Terrestrial Magnetism, a small arm of the Carnegie Institution of Washington. In 1902, business tycoon Andrew Carnegie founded the research organization to foster the needs of scientists—at first men, and then much later women—working at the cutting edge of their respective fields.

Burke was also making measurements of galactic rotation. He, however, was using a radio telescope to see how pockets of neutral hydrogen gas swirled around the heart of our galaxy. It enabled the DTM astronomer to track the velocities of galactic regions much farther out than Rubin could. Even at these greater distances, he too was seeing flat rotation curves. The results intrigued Rubin. She made a point to stop by the DTM. Striding across the facility's campus, she was struck by the group's scientific and professional atmosphere. It appeared so quaint and intimate, perhaps because DTM is nestled among the residential communities of western D.C. In that instant, the gutsy Georgetown astronomer resolved to not only discuss her data, but ask Burke for a job as well.

Burke was taken aback by Rubin's proposal. "He reacted as if I had asked him to marry me, or something," she says. Once he got over his initial shock, he invited Rubin to join him at the department's weekly communal lunch, an event where the researchers sat down to share their work with the other DTM scientists. Just as the staff was preparing to eat, the facility's director, Merle Tuve, came over. "Well, we do a lot of learning at lunch," he said, "and there is a blackboard there, so why don't you get up and tell us what you're doing." Rubin readily did as she was asked.

Tuve had a shrewd eye for scientific talent. Satisfied with the thirty-six-year-old astronomer's off-the-cuff remarks, he handed her a two-inch by two-inch photographic plate and asked if she could measure the image's spectra. "I went back to my Georgetown office, or maybe it was at my dining room table, and I measured it." Upon completion, Rubin immediately dispatched the results.

It was January of 1965.

Three months passed. The Georgetown astronomer heard nothing from the DTM staff. Then, one afternoon in March, she got a call from Tuve. He abruptly asked her how soon she could come by and talk to him about a job. "I can be there in ten minutes," she said, to which he replied, "No, I meant next week." "No," she responded emphatically. "I'll be there in ten minutes."

Rubin first showed up for work on April Fools day. It could not have been more fitting. When backing into a parking spot, she knocked over a sign. Then, upon entering the administration building to check in, no paperwork documented her ever being hired. After patiently struggling through the bureaucratic red tape, she then had to make one more decision: choosing between a desk in Bernard Burke's office, or one with Kent Ford, a young instrument builder. He, at the time, was tinkering with what he called an image tube spectrograph. "She moved in with me," says Ford, "and she has never moved since then."

Beyond the Milky Way

Pairing up with Ford and his image tube was a "gift out of the blue." Rubin did not anticipate how much the instrument builder and his device would affect her career. More important, though, the two officemates proved to be an excellent team; her passion for astronomy matched his skill with telescope hardware, and pretty soon, they were off to Arizona. "Early on, I am sure people thought it was pretty risqué for the two of us to go off into the night to the telescope," says Ford, "but we were too focused on making the image tube work and getting data to think much of it."

From the mid-1960s until the 1980s, Ford's tube was one of the best pieces of equipment to capture the photons of light streaming toward Earth from distant celestial objects. The unique aspect of the instrument, which looks like a series of small film cans glued together, was how it managed celestial light. An incoming photon collided with the innards of the instrument and generated a shower of electrons. These negatively charged particles then fell onto a phosphorescent screen culminating in a glow of light. Photographing the resultant glow, instead of the faint light the distant objects emitted themselves, made it easier to analyze the spectrum of the faint stars of a galaxy. In effect, the image tube could make any small-scale telescope as good as the mammoth two-hundred-inch reflector at Palomar mountain on the west coast.

The DTM team first used Ford's tube to hunt for astronomical beasts called quasars. These new cosmological creatures stole the scientific spotlight after their discovery in 1963. Quasars are intensely energetic galactic cores, each several millions times more massive than the Sun, that reside at the far edges of the visible universe. Finding these objects excited scientists for several reasons, but mainly these active galaxies, born relatively soon after the Big Bang, helped astronomers gauge the age of the cosmos.

The universe is expanding, puffing out like a balloon, and its fabric stretches like pulled rubber. As space-time extends, galaxies move farther and farther apart, and, because of this cosmic distention, all the distant quasars appear to be flying away from Earth. Therefore, when the light from these galactic cores actually makes it to our telescopes, its wavelengths have been stretched and stretched in the cosmic expansion and thus made redder. Astronomers realized that the farther the quasar, the bigger its redshift, and thus, the older its age and that of the universe itself.

That technological and theoretical understanding of the objects' importance put astronomers on a cutthroat quest for the farthest quasar. Just about every astronomer sought the fame of finding the most-distant galactic core. But, there was one problem. Despite the fact that each one puts out as much light as one trillion suns, the quasars are so far away that they are nearly invisible and were almost impossible to study with standard 1960s telescopic equipment.

The perfect tool to trap a quasar's faint light was none other than Ford's image tube. Vera Rubin's friends and fellow astronomers knew this. They called her constantly, always wanting to see what objects she had observed with the image tube and, of course, learn their redshift and distance. The pace became too hurried for Rubin, especially since she didn't get to the telescope that often to check her measurements. "That just wasn't the way I wanted to do astronomy," she says, explaining she feared being rushed would cause her to make errors. "I would rather drop dead than have another astronomer find I made a mistake."

Rubin withdrew from quasar research altogether. Instead, she chose to return to her beloved galaxies, where she and Ford could put the capabilities of the image tube to a different test, one where they would learn more how stars circulate within a galaxy. To quasar hunters, the subject seemed dull and overdone, but Rubin was never one to care much what other people thought. She sought the solitude of a small and less competitive project. With the support of the DTM, which gave scientists the freedom to pose all manner of research questions without the publish-or-perish atmosphere of academia, Rubin and Ford again set out west to Kitt Peak. It was 1967. The observatory had a fairly new 84-inch telescope and the two decided to use it. The larger apparatus paired with Ford's tube was perfect for the team's goal—to move beyond the Milky Way. Rubin and Ford therefore turned the telescope's eye on Andromeda, our nearest spiraling neighbor situated two and a half million light-years away.

A Startling Spin

Rubin's choice to study the Milky Way's sister spiral developed from talks with Bernie Burke and his fellow radio astronomer, Morton Roberts. Burke's work in the early sixties and several of Roberts' observations offered an early clue to astronomers—perhaps the scientific community was mistaken in there assumption that Newton's laws could perfectly predict the orbital speeds of evermore distant stars in a galaxy. That hint, however, went unheeded.

Other astronomers blamed the curious results on the astronomers' techniques. Burke and Roberts were merely analyzing the motions of galactic gas, not of stars, they countered; instrument error, misinterpretation of data, and unaccounted-for influences on the gas were inevitable. Rubin refused to accept these excuses. "I never liked to assume anything and still don't, even now." Yes, she conceded, the radio guys were working with neutral hydrogen gas, but she thought it more than coincidence that their analyses of swift gas velocities matched her findings of fast stars in the Milky Way. Her rotation curves were flat, so were Andromeda's radio rotation curves. "As soon as Burke and then Roberts started to question that idea of declining stellar velocity in Andromeda," she says, " I wondered whether I could turn the telescope at Kitt Peak on our nearest neighboring galaxy and *see* the same unexpected behavior."

Studying the foggy fringes of this galaxy was not easy compared to examining the bright central bulges of other spirals, as the Burbidges did. It certainly required a different technique compared to pegging the motions of stars in our own galaxy. The reason is because, even though Andromeda is close relative to other galaxies, its distance is still so great that even the best telescopes of the time could not resolve the light emanating from its individual stars. Invaluable to Rubin's study, therefore, was Ford's image tube. It allowed her to spy on dim, gaseous knots of adolescent stars, the fiery red H-II regions. But since these gaseous regions could not be seen directly, the DTM astronomers pointed their instruments at what appeared to be dark space. They looked at the shadowy rim of Andromeda's outer periphery, and they crossed their fingers. They waited, and they hoped they that the tube would pick up the knots' light.

"None of this stuff was here when we first did Andromeda—not the warm control room, or the electronic guider, and definitely not the computers," Rubin says, as she carries out her latest observations atop the mountain west of Tucson. "We did everything by hand."

Night after night, for hours at a time, Rubin sat in the open air, her eye pressed to the telescope, her hand on the guider. She waited and watched. Occasionally, she nudged the controls of the instrument ever so slightly to keep the galaxy in the guiding crosshairs while it, millimeter by millimeter, traversed the evening sky. "I remember tracking Andromeda. Its center had this light, greenish glow. It always made me wonders if someone, an astronomer in our neighboring galaxy, was looking down on our own and watching us."

Because the galaxy's disk lies on an incline directed toward our planet, anything moving toward Earth, including H-II regions, has its light shift into the blue part of the spectrum. The objects and regions receding from Earth, the ones rotating on the opposite side of the galaxy, emit light waves that get stretched out and hence appear redder to astronomers.

For six hours, Rubin tracked Andromeda's gaseous knots, eager to capture a spectrum across the spiral's width. When she finally finished her first exposure, the astronomer climbed down from the telescope's cage, reached in and gently unfastened the photographic plate from its resting place in the spectrograph, and then slipped down to the observatory's dark room. Inside, her hands began to tingle. Desperately, she tried not to let them shake as she treated the plate with the proper chemicals. Slowly, as if by magic, the lines of Andromeda's spectrum materialized. It was like the uncovering of a secret message scribbled with invisible ink. Rubin's trepidation turned to euphoria. At the sight of the banded lines, she knew she had the perfect procedure for measuring the motions of distant spirals.

Anxious to return to the telescope to collect even more spectra, Rubin left a visiting astronomer to finish cleaning the plate. Little did she know he was mistakenly washing away the photographic emulsion with hot water. Afterward, he was guilt-stricken, but to Rubin, losing the plate didn't matter. She was too ecstatic that she and Ford had finally found a way to probe the outer edges of far-off galaxies.

Exposure after exposure turned out as great as the first. Soon getting the spectra was second nature; interpreting them, however, was a bit puzzling. They were all so straight. Rubin was observing that Andromeda's outermost stars raced around the spiral just as fast as the galaxy's innermost stars. How, in the realm of physics, could this be? Brainstorming ideas, the astronomer began thinking in terms of what she could physically observe with a telescope. Perhaps some violent ejections of gas were stirring up the stars. Or, maybe, the gaseous knots had uncharacteristic orbits for some reason. "All my ideas turned out to be totally wrong," she says, "but I didn't know that then."

Failing to explain the non-Newtonian observations did not prevent Rubin and Ford from writing up their findings; the results were published in the *Astrophysical Journal* in February 1970. Fellow astronomers still remained somewhat skeptical. Maybe it was just a fluke, a rotation only to be seen in Andromeda. Other galaxies, they charged, would certainly not exhibit this unexpected and unexplained behavior.

Figuring out Fast Galaxies

In 1974, an even larger telescope, one with a mirror four meters or 158 inches wide, opened at Kitt Peak. Rubin wasted no time. She asked for observing time. Resolving the rotation curve of Andromeda was not enough for her, and with an instrument two times bigger than what she'd been using, she was sure she could study the bleary peripheries of galaxies other than Andromeda and our own.

"She gets enjoyment out of looking at the individual galaxies," says Norbert Thonnard, who worked as a post-doctoral student with Rubin in the 1970s. "In a way, they take on their own personalities. Studying them becomes more personal. They each teach you something."

By the mid-seventies, Mort Roberts finished further observations on Andromeda using an even larger radio telescope that had recently come online. Again, he tracked hydrogen gas and again he found swift speeds, ones that matched precisely to those Rubin had found a few years before. At the same time, Rubin was beginning to see that the rotations of other galaxies, besides the Milky Way and Andromeda, had flat rotation curves too. But yet again, fellow scientists wrote off both astronomers' findings, pointing out that they had only studied a particular type of galaxy, the kind that has a small central bulge and beautiful spiraling arms. It is the brightness of these galaxies that led skeptical scientists to question whether the flat rotation curve was a feature of all spirals or merely the most eye-catching ones.

"Nothing, no new idea, is ever well received," says Thonnard. Everyone still assumed that a galaxy rotation curve would rise rapidly and then fall off. "They assumed nature was kind," he continues. As you went outward from the center of a galaxy, its brightness dropped. Less brightness, in theory, indicated less mass, which meant the velocities of the stars far out there would drop, just like the planets in our solar system do. But, that wasn't the case. "You cannot assume anything, especially that nature is kind," explains Thonnard, who is now a scientist at the University of Tennessee. "Nature is always trying to fool you," even if other astronomers might not believe it.

The criticism fueled Rubin's determination. With the help of Ford, Thonnard, and many other Carnegie post-docs, she charged ahead, measuring the spectra in all sorts of spirals, not simply the beautiful, bright ones. She even went after velocities in more irregular galaxies, just to be certain of her conclusions, and it was during this time that Rubin grew to love how prosaic her data appeared. The curves' flatness is just so easy to see. "You could show someone a couple of spectra," she says, "and they knew the whole story." Slowly, the stories began to accumulate. First there were 20 rotation curves, then 40, and then 60. They were all flat.

The research, both radio and optical, seemed to sift down to one conclusion—something, some unexplainable force was whipping the outer stars around a galaxy as fast or faster than the inner ones. At last astronomers had to concede they had a major problem on their hands: galaxies were cranked up to phenomenal velocities. But, what was doing the speedy spinning? They did not know. Theorists, however, thought they had a clue.

While Rubin and her colleagues collected their unusual spectra, Princeton University scientists Jeremiah Ostriker, P. James E. Peebles, and later Amos Yahil contemplated the Milky Way and what makes it rotate, and they struggled to conjure up a model of the galaxy that explained why its constituent stars did not go flying off into space. For Ostriker, Mort Roberts' radio evidence was especially tantalizing. It was an added clue that a spiral needed something to stabilize it or to keep it from coming apart. It took a few years, but in 1973 the theorists officially proposed their striking hypothesis: A galaxy had a spherical fog that mingles with and envelops all the stars in a spiral, and though it is invisible and does not emit light, this cloud is vitally important to maintaining a galaxy's disc-like shape. They reasoned it had to have mass, and therefore gravity, to keep everything in. The halo locks in all the galaxy's innards. Could that be what tugs the galaxy's most distant stars along? Perhaps, said the theorists.

With that theoretical blessing, says Roberts, the floodgates opened. Astronomers began to refer to the theorists' galactic fog as a dark matter halo. They accepted as a serious possibility that an invisible mass existed in the universe. It was a throwback to the early work of Fritz Zwicky. But Rubin, Roberts, and others brought it to the forefront some forty years later with irrefutable evidence, profoundly changing astronomers' understanding of the cosmos. They, not Zwicky, eventually persuaded astronomers that the majority of the mass in the universe emits little or no light. And, they forced cosmologists, scientists who describe the nature of the cosmos, to begin speculating what could make up this extra, unseen substance.

At first, they thought that maybe dark matter was composed of ordinary stuff, basic space debris such as giant Jupiter-like planets or bunches of dead and dying stars. But, this hypothesis died relatively early, when in the late eighties and early nineties, cosmologists realized that the Big Bang did not spew out enough ordinary matter that astronomers needed to spin up the galaxies. This revelation, says MIT theorist Edmund Bertschinger, perpetuated another upheaval in science, one that completes the Copernican revolution. Not only was Earth no longer at the center of the universe, but also, its elements, the stuff scientists thought made up our total material world, turns out to be a measly fifteen percent. If space "junk" didn't make up the majority of the mass in space, then it had to be composed of some more exotic substance. The time had come to imagine an entirely new fabric for the cosmos, something all together alien to us.

Almost immediately, particle physicists began to buzz. They eagerly hashed out ideas on prospective dark matter candidates. Neutrinos, maybe. Fusion reactions inside stars spew out trillions upon trillions of these particles at a time, so, even though they are massless and barely interact with normal matter all of them added together might make up the dark matter. Or maybe not.

With the most delicate detectors, scientists eventually snagged a few of these elusive bits of material and then a few more. What physicists found when studying their sparse interactions with atoms was that neutrinos were still too light to create the dark weight of the cosmos. They were not heavy enough to stir up Rubin's stars; plus, the neutrinos flying around as relics of the Big Bang could not have brought about the bubbly, large-scale structures of galaxies that saturate the universe today. Neutrinos were out.

Next up: axions and WIMPS, or weakly interactive massive particles. Both these sub-atomic creatures should interact very rarely with normal matter and the Big Bang might have produced enough of them to serve as dark matter. Named in honor of a laundry whitener, the axion was supposed to "clean up" some messy details in quantum physics. Predicted to be lightweight compared to protons and neutrons, axions are thought to tango with normal matter only through the strong and weak nuclear forces. They also flip between being themselves or being photons when they encounter a strong magnetic field. Physicists hunting for axions today base their detection experiments on this property.

Rivaling the axion is the WIMP. Born of a different breed, this particle comes from a theory called supersymmetry, where each observed sub-atomic entity has a more massive "shadow" partner. For instance, the photon has a mate called the photino and a particle called Z has a partner called zino. The lightest of these supersymmetric particles, in general called neutralinos, are right now favored as the WIMP candidate for dark matter. They, in theory, interact with normal matter only through the weak nuclear force and gravity and do not emit light waves, so they cannot be seen by standard detection systems.

To snare a WIMP, scientists dig inward, deep within the bowls of the Earth. Only there can they arrange an experiment with the necessary precision to catch a neutralino. Buried half a mile underground in an abandoned salt mine in Minnesota is the Cryogenic Dark Matter Search, for instance. The depth protects the equipment from any radiation that might upset the detection experiment. WIMPs must be at least a hundred times more massive than protons to account for all the dark matter in the universe and its associated gravitational pull. With this bulk, they should collide with germanium in the underground detector set up in Minnesota, possibly a couple of times each year. Infrequent and subtle as that may seem, getting a WIMP to smack into a germanium nucleus would be like taking a baseball bat to a gong. The crash sets off a quivering that would reverberate through the germanium, ultimately letting the experimentalists "hear" the WIMPs "ring."

As of today, no one has convincingly caught an axion or a WIMP, although Italian physicists claim they have detected the latter twice in the past eight years. Yet, despite disappointment so far, scientists still design and build new experiments every year looking for these dark matter particles, says Jocelyn Monroe, an MIT particle physicist. In fact, she and her colleagues are attempting to build a sensor that would measure how the mere motion of Earth through our galaxy kicks up a breeze of dark matter particles. It shoots them in the opposite direction of the planet's motion. Figuring out which way this wind blows will help scientists distinguish background, or terrestrial noise, from a dark matter particle's signature sound.

With so many instruments and so many professional careers invested in this new particle physics venture, says Rubin, "that's a faucet that will be hard to shut off." Her seemingly "dull" investigation of individual of galaxies was the first turn on the nozzle; her project proved not to be boring after all. Rubin's observations told scientists that dark matter is what holds them together and is what allows them to form in the first place. They are what let astronomers assume dark matter is there. That is, of course, if it exists at all, says Rubin.

A Real Dark Matter

Everyone believes in dark matter. Well, almost. "There are some, probably less than a dozen or so, that think Newton's laws don't hold at distances far from the center of a galaxy," Rubin says. *They* don't see the need for a mysterious new particle.

Leader among the skeptics is Mordehai Milgrom; to him it is a bit illogical to use Newton's laws, strictly as they were written in the seventeenth century, to work out galaxies dynamics. While these laws may be reliable when dealing with, say, the solar system or an apple falling to the Earth, Milgrom thinks they may actually break down in the vastness of space where gravity is barely expected to exist. In response, the Israeli astrophysicist modified Newton's laws. He tweaked them a bit, just as Albert Einstein had done it in the early twentieth century. Milgrom's solution to explain Rubin's rotation curves was MOND, or Modified Newtonian Dynamics, and, surprisingly, in the 1980s the adjusted arithmetic did demonstrate marginal success in reconstructing their signature flatness.

"Milgrom's model wasn't very popular," says Ed Bertschinger. The twinge of doubt the Israeli scientist placed on the existence of missing material in the cosmos did not stop particle physicists from launching their experiments to trap a dark matter particle. Nor did MOND keep observational astronomers from continuing to study how the elusive, invisible material affects spiral and elliptical galaxies and even tiny, dwarf galaxies, places where astronomers believe dark matter acts as a lens, magnifying and distorting the looks of far-off galaxies and clusters.

"Personally, though, I am happy that some brave souls are looking into modifying Newton's laws," says Rubin. "I mean the fact that the laws would not hold at low accelerations (where there is little seen mass and supposed gravity) seems to me to be perfectly normal, at least, at some level."

The greatest criticism of MOND is that it has yet to be reconciled with Einstein's general theory of relativity, a far more detailed explanation of gravity, and one that has so far passed every challenging scientific test it has faced. "Still there is no reason that life has to be so simple to work, that we have to have this dark matter as the only answer to explain the rotation of a single galaxy," says Mort Roberts. "Now, I am not confirming Milgrom's model by any means, I am just saying that every time someone announces the death of it, it keeps on living."

It's physicists like Fred Cooperstock and other "brave souls," as Rubin calls them, who keep MOND and other alternatives to dark matter from dying. "This idea of having all this stuff all around me, supposedly six times more than the matter we can see, and having no way of seeing it makes me really uneasy," Cooperstock says. "I am a conservative person, so conservative, some might consider me to be a radical."

The University of Victoria theorist wants to stick to the laws that work. Everyone has been using Newtonian gravity to explain the rotation curves and galactic clusters' swift speeds. That puzzles Cooperstock a great deal. "They know that general relativity is, right now, the better, in fact, the best theory of gravity," he says, "so why not see if general relativity gives a different answer?"

Scientists typically reserve general relativity to describe situations where gravity is intensely strong, such as near a black hole or where energies and speeds of particles are very high. But, with help from of his post-doctoral fellow Steven Tieu, Cooperstock applied Einstein's equations to galactic dynamics. The theorists reason that these calculations work because of general relativity's apparent "non-linearity," which is what distinguishes it from Newton's theory of gravity.

Einstein's math is not based on simple addition, Cooperstock explains, but Newton's is. With Newton's equations, if you have two objects and you combine the attractive force of the first object, "A," with the attractive force of the second one, "B," you get the net effect—"C." C equals A plus B. The mass of the galaxy's core plus the mass of the stars gives the gravitational force, which ultimately determines the stars' orbital velocities. Einstein's equations are very different. The overall equations of general relativity tell you what effect each object is having on another. You can't just add A plus B. The math is far more complex.

That is why Cooperstock and Tieu were somewhat surprised when, in 2005, they applied Einstein's equations and were able to reproduce models of flat galactic rotation curves. Upon publication, immediate and harsh criticism resulted; other scientists charged that their calculations still left room for additional material, even perhaps some dark matter. To counter this disapproval, Cooperstock and Tieu went beyond their static model of a galaxy, one that spins on its axis without ever changing. They inserted a dynamic component: time.

Rather than study an ideal model of a single galaxy that spins forever without change, the considered a model of a spherical cluster of millions of galaxies that fall toward the center of the cluster. "It's an evolving picture in time," Cooperstock says. At its essence, the simulation represents the spirit of Fritz Zwicky's missing mass problem as the Caltech astronomer originally saw it, except that Cooperstock and Tieu achieved galactic clusters' high velocities without dark matter to drive them.

Throwing together millions of collapsing elements that look like digital dust balls, the two physicists wanted to see how Einstein's theories explain the effects that each dust ball, each galaxy representative, has on those around it. So far, the scientists say, they have had success. They have accounted for the higher-than-expected velocities using everyday matter, not the invisible material that is currently in vogue. But, before Cooperstock and Tieu challenge astronomers to throw out dark matter all together, the theorists suggest that they need to run many more simulations and that scientists should attempt to devise small-scale experiments where they account for gravitational collapse and test general relativity.

"Very few dyed in the wool astronomers really understand general relativity. They don't know how rich it is, so they are ready to jump on the dark matter bandwagon." But to Cooperstock, saying we see a speck of real matter and the other ninety-some percent is some unseen stuff, is illogical. "When they say that, I start smelling a rat."

Four Decades and Still Going at It

Ominous, gray clouds cover the evening's sky at Kitt Peak. The seeing is not good. "Maybe it will get better as the temperature drops," Rubin says to Hunter as she tugs at her coat zipper. The elder astronomer seems fatigued, and a look of worry sets across her face. Her eyes are distant. They reveal an intense longing.

A few hours earlier, Rubin spoke by phone with her husband of almost sixty years. For the past eight years, he'd been battling a debilitating form of bone cancer. During much of that time, Rubin had not left her husband's side. Choosing to forego observing runs, she would instead analyze her data and do her research only at DTM, which is just a few blocks from the couple's home. That way, if he needed her, Vera could get home to Robert quickly.

During the previous few months, from about September on, Rubin's husband had been doing quite well, she says, and his health seemed to be improving. By November, she felt confident she could leave him for two weeks to come out to Kitt Peak. Unfortunately, Robert was now suffering severe pain, but Rubin, thousands of miles from home, could do very little to care for him.

To divert her attention, the astronomer checks the weather forecast. Tonight and tomorrow are her last two in the fourteen-night observing run she is doing with Hunter. Cloudy, tonight; partly cloudy, tomorrow, the forecast reads. Perhaps she should leave in the morning, she muses aloud.

Silence.

Rubin's eyes close. After a few moments, she begins to reminisce about the days when she felt like a pioneer, the days when she literally looked up into the sky, fought the cold, and guided the telescope with her bare hands. Her first time at Kitt Peak was nearly half a century ago. Rubin remembers it vividly. Peering through the eyepiece of the 36-inch telescope, she was tracking stars as they traversed the sky. She was gathering data on the Milky Way. Former observatory director, Nicholas Mayall, came to check on her. She told him just how wonderful it was to be out there. Without hesitation, he replied, "That is what happens when you pour a million dollars onto a mountain top."

Another beep.

Rubin's eyes shift to Hunter's computer screen where the swirling giant, the galaxy UGC 2885, pops up on the screen. This galaxy is times ten bigger than the Milky Way. It is the largest spiral found to date. At a breadth of 815,000-light-years, the stars in the outermost regions have undergone a mere seven revolutions since the beginning of universe.

In that time, our own galaxy has rotated some fifty times. Despite so few complete turns, the spiral arms of UGC 2885 are startlingly smooth and well developed, says Rubin, her voice carrying a hint of excitement.

The last time she studied this galaxy, twenty some years ago, she was startled to find such perfection in the arms. She questioned how such symmetry could happen. It could obviously not be a result of multiple rotations. That she knew. Perhaps, it has something to do with the stars of the spiral. The cocoons holding its nascent stars circle the galaxy's outer edges at similar or somewhat quicker speeds than the stars circulating closer to the center. It's these curious characteristics that keep Rubin coming back to Kitt Peak. But, there is something else too. Rubin also returns because she says she is never sure how many more times she will get to study the heavens through the eye of a telescope.

She hopes to better explain her beloved galaxies' shape, formation, and evolution. To her it seems so terribly obvious to keep pushing the limits. New detectors and cameras make her think it is possible to find a galaxy's most remote H-II regions. Finding them would let Rubin draw out the galaxy's rotation curve to a distance up to three times greater than what is now known and finding them would tell astronomer more about the invisible mass that tugs them along.

Even today, after years of research, astronomers still do not know how dark matter distributes itself in the cosmos. To understand if there is more invisible material at the galactic edges than closer to the center, scientists slice up galaxies, drawing them like layers of an onion. They want to see if a galaxy's inner peelings have less dark matter than its outer shell. Probing more deeply, Rubin hopes to find more stars and to measure if they are fast or not. Her observations will determine where a galaxy's cloud of dark matter finally drops off—or, if it does at all.

Right now, scientists are not sure if dark matter halos ever end. But if, for example, our galaxy's halo reaches farther than scientists think, it could be big enough to touch Andromeda. Some scientists believe this to be a fact, and, if they can observe it, says Rubin, "it could mean that there is no place in the cosmos that is without dark matter."

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