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SPRINGTIME FOR NEUTRINOS

Next to the question of why there is anything at all, the identity of that anything might be the most fundamental issue that science could hope to confront—and one that astronomers might well have thought they had already answered. Since Hubble's time it was accepted that the universe was stars and galaxies and dust and gas and dirtball rocks of planets, orchids, algae, and human beings. It was a woman who played the leading role in convincing them that astronomers were wrong; they had no idea what most of the universe consisted of. Most of the universe was not stars and galaxies. Most of the universe was invisible.

Vera Rubin was on the run when she discovered dark matter. Trouble and controversy had dogged her career. Part of it was because she was a woman; part of it was because she was good. All she wanted to do was observe her galaxies in peace, but she seemed to have an unerring knack for stumbling on disquieting observations.

Rubin doesn't look like a troublemaker. Short, with a round face and a white-haired butch haircut, she is a grandmother and plain spoken. Growing up in Washington, D.C., she became entranced by astronomy from watching the stars go past her bedroom window. Rubin went to Vassar and was a member of the class of 1948, which was immortalized in Mary McCarthy's famous novel *The Group*. Rubin was attracted there by the fact that an earlier Vassar graduate, Maria Mitchell, had been the peditions begin; and it is where Rubin and Ford tried to plot their first rotation curve, in 1970. Andromeda was too big to cover in one exposure with the spectrograph; they had to tiptoe star field by star field through the galaxy over many nights of observing.

When they completed their survey, however, a curious thing happened: Rubin lost her first chance for immortality. After fitting all these observations methodically together into one long sinuous plot, she and Ford noticed that the star speeds did not slow down in the outer regions of the Andromeda galaxy. In astronomical jargon, the rotation curve was flat. It meant there was something going on next door in the nearest, most well-observed galaxy in the universe that nobody understood

But there was no "eureka." "We weren't wise enough," said Rubin a little ruefully, shaking her head, at a loss to explain their lack of perception any further. The full meaning of rotation curves had not quite sunk in yet. It didn't occur to them to connect the flat curve to the distribution of matter. After puzzling about the possibility of some kind of feedback effect that would regulate the stars' speeds, they dropped the subject.

Rubin and Ford went back to using their splendid image tube spectrograph to measure redshifts of spiral galaxies. Of course, they bumbled right back into the lopsided expansion of the universe that Rubin had unhappily discovered in graduate school. This time it got a name: the Rubin-Ford effect. The simplest interpretation of this effect was that a sizable chunk of the local universe, in addition to expanding, was being pulled by something and sliding in the general direction of Pegasus. This discovery had few fans among senior astronomers. Sandage, having established the uniformity of the expansion of the universe to his own satisfaction, suspected that Rubin's sample of galaxies was biased.

With a storm cloud over her head, Rubin and Ford, along with Norbert Thonnard and David Burstein, returned to their spiral galaxy dynamics, where the puzzling rotation curve of M31 lay in wait like a ticking bomb. This time they decided to do a thorough job of investigation. They would go through the spiral galaxy types systematically, starting with the most luminous ones, take spectrographs, and analyze the star motions. For a small or distant galaxy, this was a one-step job. When the entrance slit of the spectrograph was lined up with the long axis of the galaxy, the blueshifting of light from stars at one end of the disk coming toward us and the redshifting of light from stars going away at the other end twisted all the spectral lines into S-curves. The galaxy's rotation curve could be read off a single spectrogram.

As soon as Rubin and Ford began eagerly holding up freshly developed spectrograms in the darkroom and squinting at the curving spectral lines, they realized that something strange was going on. The rotation curves did not trail off the way they were supposed to; instead, they were flat, like M31's. The stars were not slowing down at the edges of the galaxy, where there was presumably little additional mass to propel them. If anything, they speeded up, as if the farther out in the galaxy a star lived, the more and more mass was available to whip it around faster and faster. But out there was less and less light, so what *was* the additional mass that was propelling the distant stars? "This time," said Rubin, "we knew immediately we had something phenomenal."

There could be only two explanations for such behavior. Eithe Newton's laws were wrong, or there was something else in the galaxy—something that was not luminescent, and that was not concentrated at the center of a galaxy, as the stars were. Rubin calculated how much of this extra "dark" mass would be needed to whip the stars around at the speeds they were traveling and keep the rotation curves rising. The answer was astounding: two to ten times more mass than seemed to exist in the visible galaxy.

"Great astronomers told us it didn't mean anything," Rubin said. "They said it was an effect of looking at bright galaxies." Go look at dim galaxies, she was advised.

So she did. She was not backing down this time. Rubin suspected that what she had found was the missing mass.

"Missing mass" was a term that had been coined by the irascible Fritz Zwicky to describe the results of a disturbing observation that had been made back in the thirties, and it had been tugging anxiously at the minds of thoughtful astronomers ever since.

Zwicky had measured the redshifts of a bunch of galaxies in the Coma cluster, figured out how fast they were moving with respect to one another, and calculated how much gravitational force would be required to keep the cluster from flying apart. Then he compared this gravitational mass to the luminous mass of the cluster, which he obtained by simply adding up all the starlight. To his surprise, the gravitational mass outweighed the luminous mass ten to one. The conclusion was inescapable: unless the Coma cluster was just a temporary optical illusion, 90 percent of the Coma cluster—and, it turned out, of other clusters—was invisible.

Zwicky called the invisible 90 percent the missing mass. It would prove to be his most lasting and damaging swipe at the cosmological establishment. The bottom-line implication of Zwicky's work was that astronomers didn't know what the universe was made of.

Like most astronomers, Rubin had gone through the exercise of redoing Zwicky's calculations in graduate school and concluded there was something not ready to be understood there. Since Zwicky's time, astronomers had found other examples of collections of galaxies that seemed to weigh more than the sums of the individual galaxies inside. In general it seemed that the larger the system being studied, the bigger the discrepancy was between visible and invisible weight—the more missing mass there was. Some astronomers clung to the hope that, on the largest scales, there would turn out to be enough missing mass to close the universe.

Peebles had an influential hand in this interest in missing mass. In 1973, during the period when he was enamored of numerical simulations on computers, he and a Princeton colleague Jeremiah Ostriker had attempted to simulate the structure of a spiral galaxy on a computer. They tried and tried, but kept failing. The disk of the galaxy, it seemed, was unstable; the gravitational forces between the stars in the disk pulled it apart. How was it then, that galaxies existed? Eventually, Peebles and Ostriker found that the disk would be stable if it was surrounded by a spherical halo of other matter, like a hamburger patty sandwiched between two halves of a bulky roll. Such a halo would naturally have to be invisible, and it didn't have to be very massive to stabilize the galaxy. Peebles recognized that by supposing that the dark halo was arbitrarily large and massive, he could in effect add enough invisible mass to galaxies to close the universe, although there was no evidence that so much was there. He and Ostriker had to hold themselves back from imputing too much dark mass to the halos when they wrote their paper.

A year later Peebles and Ostriker addressed the question of dark matter, galaxy masses, and omega head on, with the help of Amos Yahil, a young Israeli particle theorist on a postdoc. They analyzed all the different ways in which galaxy masses had been measured—from visible starlight to the dynamics of double galaxies orbiting each other and large groups. They found that as astronomers looked on larger and larger scales, the masses of galaxies seemed to go up. They concluded that Zwicky had been right, that galaxies were probably ten times as big and massive as they looked. Outside their own department, this was not well received. Princeton theorists had the reputation of favoring a closed universe, both because of Wheeler's predilection and because the galaxy correlation statistics pointed to a dense universe.

As it turned out, a spherical halo of dark matter fit Rubin's observations very well. She and her crew spent the next few years shuffling back to telescopes in Arizona and Chile filling out their repertoire of galaxies: dim galaxies, bright galaxies, loose spirals with anemic cores and tight spirals with arms, barred spirals, spindle-shaped galaxies. They collected a great variety of rotation curves. Rubin became expert at reading their nuances. She bragged, "If you give me a rotation curve and the

Hubble type of a galaxy, I can tell you the mass, luminosity, and radius of the galaxy."

What they all had in common was the signature of missing mass or dark matter, the stars whirling faster than the gravity of the stars alone could make them; luminous matter was like a kind of foam on a dark mystery wave. "Nobody ever told us all matter radiated," she blurted in her blunt style, "we just assumed it did."

Rubin concluded that what astronomers call galaxies—the spidery curls of starlight and gas—were in fact only the luminous cores of much larger, darker, and more massive clouds. She developed a kind of stump speech about her work that she titled "What's the Matter in Spiral Galaxies?" Dark matter, she said, appeared to surround and permeate a visible galaxy. Within the visible boundaries of the typical spiral galaxy Rubin estimated that about half the mass was dark matter. But there was every indication that the dark cloud extended even beyond the visible edge of the galaxy; its ultimate dimensions could not be traced. Dark matter could, as Zwicky's much earlier findings suggested, and Ostriker, Peebles, and Yahil had repeated, outweigh luminous matter 10 or even 100 times to 1.

Rubin's main point was philosophical. For 300 years astronomers had been presuming that the universe was what they saw. What they spent their time doing was sorting lumps. Atoms formed into stars, stars formed into galaxies, galaxies into clusters, clusters into superclusters, maybe. Now this woman was claiming that the cosmos was what they did *not* see.

"When we view the sky with our eyes, with a telescope, or with a photographic plate, what we actually see is that the distribution of *luminosity* is clumpy," Rubin said, leaning heavily on the word "luminosity," as if it were suspect. "Is there valid evidence that the distribution of optical luminosity describes the distribution of matter? The answer to this question is a resounding no."