Vera C Rubin (1928–2016)

Then even nothingness was not,
nor existence,
....
At first there was only darkness
wrapped in darkness.
All this was only unillumined
water.

Rg Veda, As quoted by Vera Rubin at IAU Meeting, New Delhi.

Science, once in a while, takes great leaps forward. Sometimes through brilliant flashes of insight that illumine a backdrop of knowledge acquired through hard groundwork. Sometimes through meticulous data, which is incontrovertible due to the hard groundwork and the deep insight that goes into the obtention, characterization and analysis of it. Vera Rubin's landmark work, pointing out the flat rotation curves of spiral galaxies and the non-Keplerian motions these implied, falls in the latter class. Through her work, dark matter entered our consciousness as the dominant component of the Universe, relegating the familiar visible component to a mere less than 10 percent of the total.

Autobiographical sketches of eminent astronomers grace some of the volumes of *The Annual Review of Astronomy and Astrophysics*. 'Cosmology', 'dark matter', 'family', 'galaxies', 'rotation curves', 'students' – so goes the keywords to the biographical sketch Vera gave to the *Annual Reviews* in 2011. She titled it 'An Interesting Voyage'. Vera Florence Cooper was born in Philadelphia in 1928, of Jewish parents, Rose Applebaum, whose mother had immigrated from Bessarabia, sailing alone to the US at age 16, and Pete Cooper, born Pesach Kobchefski, who had reached the US at age seven to join his father who had immigrated to the US a year or two earlier from Latvia. Their two children, Ruth and Vera, grew up through the Great Depression, amid a cheery scatter of grandparents, aunts, uncles, and cousins, shielded from the financial difficulties of the time.

Vera Cooper and Robert Rubin were brought together by the two sets of parents who had 'a daughter in Vassar' and 'a son in Cornell' each. They married within three months of meeting each other, a marriage that turned out to be a very happy one. In Sanskrit it would be said they were 'manonukula' to each other. It was under the support of Bob's gentle persistence that the mother of the young and growing family, who wanted to learn more, enrolled for a graduate program in Georgetown University. Later on, Bob is known to have arranged his life so that Vera would get good research opportunities at telescopes in the US and Chile. The quality of generous mutual help that constituted the basis of their happy work life balance may be inferred from Vera's own words, quoted below. She had enrolled in the graduate school at Georgetown University, the only university in the area that offered a PhD in astronomy. The classes were taught by eminent scientists located in the area.

At Georgetown University, all graduate courses were at night. This is how I (pregnant, not driving) got to Georgetown, twice a week from 1952 to 1954. After work, Bob picked up my mother and drove her to our house, she carrying dinner for my father and herself. At our house, she got out of the car and I got in, having fed the child (later children) and carrying dinner for Bob; he ate dinner in the car after I had gone into the Observatory.

– Rubin V,
An Interesting Voyage, *The Annual Review of Astronomy and Astrophysics*, 49;1, 2011

Robert Rubin studied physics in Cornell University, under Nobel Prize winners Richard Feynman and Hans Bethe, theoretical astrophysicist Philip Morrison, and probability theorist Marc Kac. He completed his doctorate in chemistry under Nobel Prize winner Peter Debye in 1951. His work crossed traditional disciplines of physics, chemistry and mathematics. When researchers at the National Institute of Health (NIH) expressed interest in what he was doing, Rubin taught himself biology and joined NIH. He was a fellow of the American Physical Society and the American Association for the Advancement of Science and president of the Philosophical Society of Washington. He was also a member of the American Chemical Society, the Biophysics Society, the American Mathematical Society, and the Society for Industrial and Applied Mathematics (Patricia Sullivan, *Washington Post*, February 5, 2008). Vera Rubin was a member of the National Academy of Sciences, the Pontifical Academy of Sciences, and the American Philosophical Society. She won the Gold Medal of the Royal Astronomical Society in 1996 – the first woman to be so honoured since Caroline Herschel in 1828, and the US National Medal of Science in 1993 among many other awards and honours. She was the second woman astronomer to be elected to the National Academy of Sciences.

After a BA in astronomy from Vassar (1948) Vera enrolled for her MA in Cornell. Her Master's thesis (1951) explored the deviations of the motion of galaxies from the Hubble flow. She returned to this later in the 1970s. At Georgetown University, with George Gamow as her advisor, Vera worked on the distribution of galaxies, concluding that rather than being distributed uniformly, they clumped together (1954). The subject of large scale structure of the Universe was taken up seriously by the scientific community only in the 1970s. Curiously, it was then seen that deviations from the Hubble flow were related to the clumping of galaxies. Defending her thesis in 1954, she was offered a position the very next year by Georgetown University, which she held for the next ten years. Her work in 1962 (along with the graduate students of her statistical astronomy class in Georgetown University) obtained a flat rotation curve for the Milky Way Galaxy. She had used published data on stars distant from the center of the Galaxy. The results were dismissed as probably incorrect or may be the data was not good enough.

In 1965, recognizing that observing was very important to herself, she gave up teaching, and asked for and obtained a job at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington, close to where Robert was working. The department had till then been all male! She worked on one-third pay so that she could be home by 3.30 pm when the children would be home from school.

With DTM staff member Kent Ford anxious to test the limits of his image tube spectrograph that cut observing times by a factor of ten, and Vera Rubin anxious to obtain new information on galaxies, the duo went to work, obtaining spectra of many galaxies, plus dozens of quasi-stellar objects, radio galaxies, faint blue objects, and planetary nebula and published nine papers by 1968. By then, the field of studying large scale motions in the Universe was becoming very competitive, and realizing that she wanted to do astronomy in a less competitive atmosphere, Vera decided to complete her study of the nearby Andromeda galaxy and obtain its rotation curve.

In an initial try, for identifying emission regions for this purpose, they observed one night in -20^{o}C temperatures at the US Naval Observatory Telescope in Arizona, but were frustrated in their attempt. Winding up in the morning, they were fortuitously guided by astronomer Gerald Kron to the magnificent plates of the Andromeda made by Walter Baade in the 1940s using the 100-inch Mount Palomar telescope. After identifying the locations of the emission regions and three guide stars for each, observations were made at the Kitt Peak and Lowell Observatories, mostly blindly since the spectrograph could record spectra of emission regions and stars which the telescope could not see. The positions of three guide stars would be worked out precisely earlier, the final arithmetic done with freezing hands under a weak light at the telescope, and the telescope slowly turned to get the invisible emission region at the exact center of the field. The DTM spectrograph was carried back and forth by truck between the two observatories, the Native Americans employed at the observatories commenting that "there must be a better way to make a living". Measurements were made using the DTM Mann two-dimensional measuring machine.

Rubin and Ford obtained a flat rotation curve for Andromeda too, out to 24 kilo parsec from the center, and calculated that the mass contained within a radius was increasing with the radius. The currently popular explanation for this is that dark matter is smoothly distributed throughout the galaxy such that the mass increases linearly with distance; the matter obeying Newtonian gravity. There still is no direct observation as to what dark matter exactly is. The landmark paper was published in 1970 in the *Astrophysical Journal*. This rotation curve gained a little more attention than the first one she got. It was followed up by 21 cm observations which revealed the same flatness for the rotation curve out to a distance one-and-a-half times more than what Rubin and Ford could get in the optical. Although Babcock in 1939, Oort in 1940 and Mayall in 1951, had each put forth suggestions that galaxy observations suggested that new dynamics / matter with high mass to light ratio needed to be thought of, Vera's observations were not taken seriously. Dark matter obeying conventional gravity, as the curious 'something' which gives rise to this curious rotation that is inconsistent with our expectations regarding the behavior of galaxies, would become a legitimate subject of study only by the mid 1980s! It must be one of the more interesting quirks of human history that a fundamental discovery of cosmic gravity was made from the Department of Terrestrial Magnetism!

Vera, who was sure of her data, went on to observe more and more spiral galaxies. They all consistently showed similar flat rotation curves, reiterating the mystery that has since been called dark matter. And more than half a century after her discovery, matters continue to remain dark regarding this dark matter which suffuses our thoughts regarding the Universe. Matters continue to remain dark in the case of dark energy too, the mysterious 'something', which, may be due to the past experience with dark matter, was readily prescribed as the cause of the 'accelerated expansion of the Universe'. An acceleration in the expansion of the Universe was proposed to understand the unexpected faintness of Type Ia supernovae hosted by galaxies with high redshift (see Patrick Das Gupta, *Resonance*, Vol. 17, No. 3, pp 254–273, 2012). Dark energy, theoretically designed to be repulsive, when it starts dominating the scene, overcomes the mutual gravitational attraction of matter and produces acceleration in the expansion of the Universe. Thus dark energy became the curious something which gives rise to the curious acceleration that is inconsistent with our expectations regarding the behavior of the Universe. The superb data on Type Ia supernovae, acquired with sophisticated telescopes on the ground and in space, and using new digital imaging sensors were processed and analysed using powerful computers by two separate teams. The results, announced within weeks of each other in 1998, was graced with the award of the Nobel Prize in Physics for 2011, to Saul Perlmutter, Brian P Schmidt and Adam G Reiss "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae". It was widely felt that if dark energy deserved a Nobel Prize within a few years, there was no reason why dark matter should not be considered for one, at least after 30 years!

In a long career, Vera had observed galaxies, looking at their own motions as well as characterizing the motions within them. She observed unusual and interesting galaxies too, while continuing with her observations of rotation curves. In 1973, with daughter Judith Rubin joining in, Vera had returned to the study of the cosmological motion of galaxies (Rubin V C, Ford W K Jr, and Rubin J S, *Astrophysical Journal Letters,* 183, L111 (1), 1973). Rubin, Ford and Rubin (RFR) published data that seemed to suggest an anisotropic expansion of the Universe. This was called the Rubin–Ford Effect. The RFR data was however, later shown to reflect an inhomogeneity in the galaxy distribution in the region of their sample of galaxies (Fall S M and Jones B J T, *Nature,* 262; 457, 1973). At the age of 63, she discovered cospatial counter-rotating stellar disks. Years before her discovery, Alar Toomre (*Astrophysical Journal*, Vol.259, pp.535–543, 1982) had discussed counter-rotating galaxies as 'elegant curiosities' that would require 'considerable care to notice, let alone measure', and Donald Lynden-Bell's first paper had theoretically turned around half the stars in a galaxy, and checked whether it would be stable! Vera studied polar ring galaxies pointing out that the equality of stellar speeds at equal distances from the centre of the galaxy, along the disk and along the polar ring, suggested spherical symmetry of the halo mass distribution. She studied resonance rings in ring galaxies. The dynamical problems involved in the formation of such kinematic curiosities, like disk merger without disk destruction, the formation of polar rings and/or counter-rotating stellar disks in triaxial halos, etc., became subjects of intense study later (see for example Sridhar S and Touma J , *MNRAS* , 279, 1273, 1996).

Rotation curves were observed out to far distances from the galaxy centre to characterize the halo mass distribution as well as to look for any connections of the luminous mass distribution with that of the halo. Massive black holes at the centers of galaxies were explored by observations of circumnuclear rotation. In fact an article in *The Annual Review of Astronomy and Astrophysics* by Sofue and Rubin points out the multiple uses of rotation curves.

...kinematic tracers, in relation to galaxy properties, such as Hubble types, activity, structure, and environment. ...Rotation curves are tools for several purposes: for studying the kinematics of galaxies; for inferring the evolutionary histories and the role that interactions have played; for relating departures from the expected rotation curve form to the amount and distribution of dark matter; for observing evolution by comparing rotation curves in distant galaxies with galaxies nearby.

– Sofue Y and Rubin V,
Rotation Curves of Spiral Galaxies,*The Annual Review of Astronomy and Astrophysics*,
39;137, 2001.

It was aptly pointed out by science writer and geophysicist Mika McKinnon in a tweet that "she made science kinder and the culture of research more human". She made an inalienable space for women in science, outliving and countering the derogatory comments her high school physics teacher made about women in science. We are lucky that she didn't pay heed to his caution "you should do okay as long as you stay away from science", when she told him that she had gained a scholarship to the very selective Vassar College for women. After her BA in astronomy from Vassar, she had wanted to enrol into graduate school in Princeton, but couldn't because women weren't allowed into the graduate astronomy program there (the restriction was lifted in 1975). She presented her Master's thesis, done in Cornell, on the clustering properties of galaxies, at the Haverford meeting of the American Astronomical Society (AAS). Her parents drove the young family, which included a newborn baby, from Washington DC to Ithaca, and then across the snowy New York hills. The chairman of her department had in fact offered to present the paper for her, but, in his own name since she would be having her newborn baby, and anyway she wasn't a member of the AAS! She was the first woman who was formally authorized to observe at Palomar in 1965. The male astronomers had felt delicate about accommodating a woman in the telescope building. With good humor, she did away with the need for the restrictions that were put on access to the floor she was accommodated in, by sticking the cut out of a skirted woman to the door of the toilet on her floor. The building used to be referred to as the 'Monastery'! She was a mentor and a role model for generations of women scientists. Vera persistently and continually pointed out, and strove to get corrected, the inequality with which the scientific community treated the women among them.

Her life was enriched by friendship with all the major astronomers of the day starting with Jan Oort, Geoffrey and Margaret Burbidge to physicist John Bahcall, and Carnegie trustee William T Golden. In turn, she enriched the life of various students who had come to her at DTM and elsewhere during interactions – Sandra Moore (later Faber) as summer student going on to become University Professor and Chair of the Astronomy and Astrophysics Department, University of California, Santa Cruz, Sandro O'Dorico later going on to design big telescopes at the Max Planck Institute, Deirdre Hunter who joined Vera as a postdoctoral fellow and later became an astronomer at the Lowell Observatory, to name a few.

Vera Rubin had started tracking the revolutions of the celestial orbs as a young girl, watching the wonder of the diurnal and annual motion of the stars, through the northern windows of the bedroom she shared with her elder sister. At age fourteen, she had started taking star trails with the telescope she had built with the help of her father. The art of science lies in asking the right questions and then trying to find the answers for them. Starting as a child, watching the moon sitting steadily at the window of the bus she rode home from her grandparents and asking "how does the moon know that we are going home?" she asked questions of nature that thrilled her all along the interesting voyage that lasted 88 years. The questions with which she delineated her invited talk on 'Dark Matter in the Universe' at the International Astronomical Union meeting in New Delhi in 1985, remain as relevant today as then.

Like Tycho Brahe, Vera Rubin with her data, brought about a Copernican change in the way we think about the Universe, introducing the new component, dark matter. She changed the face of physics and astronomy, spawning a number of new fields of exploration – effect of dark matter on the nature and evolution of the Universe, on the cosmic microwave background, on the formation of the first stars, stellar clusters, and galaxies, and efforts to understand the nature / capture dark matter particles, etc.

Choosing to work on problems where there was little competition and maintaining a good work life balance with the help of a supportive family and husband, she made great strides in her chosen field while raising four children who later became scientists in their chosen fields – David Rubin became a geologist for the US Geological Survey, Judy Young, an astronomer at the University of Massachusetts at Amherst, Karl Rubin, a mathematician at the University of California at Irvine, and Allan Rubin became a geologist at Princeton University.

Till the time of her demise on Christmas day in 2016, she was waiting for a breakthrough in understanding the mystery, which she had brought to the notice of humanity, with the data she had produced, and which she wanted to be remembered by. We are still waiting.

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