Vera C. Rubin: Pioneering American astronomer (1928–2016)

Neta A. Bahcall[a,1]

Vera Cooper Rubin, an icon of astronomy whose work revolutionized our understanding of the universe by confirming the existence of dark matter, passed away on December 25, 2016 at the age of 88. Vera had a lifelong love of the cosmos. "How could you possibly live on this Earth and not want to study the universe?" she wondered. Vera was a devoted champion of women in science and a beloved role model to generations of astronomers. The astronomical community has lost a pioneering scientist; her colleagues have lost an inspiring leader and a friend.

Vera's pivotal work in the 1970s established that the orbital speeds of stars in the outer parts of galaxies remain constant to large distances (known as "flat rotation curves"), rather than decline as expected from Newton's law, and as observed in the outer parts of our Solar system. This excess speed requires excess mass beyond what we see in stars and gas. Vera's observations provided crucial and convincing evidence for the existence of this excess "dark matter," a suggestion first made by astronomer Fritz Zwicky in 1933 based, similarly, on large velocities observed in clusters of galaxies. Vera's flat rotation curves implied that galaxies are embedded in large dark matter halos; we now know that these halos contain most of the mass in the universe.

Vera's observations were carried out in close collaboration with her colleague Kent Ford, who built the sophisticated spectrograph that enabled these precise measurements. Their first results, in 1970 (1), were for our nearby Andromeda galaxy. At that time, rotation curves were also being observed with radio telescopes, tracing the rotation of the neutral hydrogen gas disks that surround spiral galaxies; these observations, carried out by Morton Roberts (2, 3) and others using the 21-centimeter line of neutral hydrogen, found similar results. Vera and Ford's observations of the stellar rotations, using optical telescopes, were less prone to interpretation of gas dynamics. Both sets of observations ultimately revealed the striking constant rotation speeds of galaxies, thus the need for dark matter. Rubin and Ford's observations of a large sample of galaxies in 1978 (4), all showing the same remarkable flat rotation to large distances, were crucial in confirming the existence of dark matter and the large dark halos around galaxies.

Vera C. Rubin. Image courtesy of Mark Godfrey (photographer).

We now know that most of the mass in the universe, 85%, is dark matter; it profoundly affects the evolution of the universe and the formation of structure. The dark matter is believed to be a new, exotic, yet undetected nonbaryonic particle, not the familiar atomic elements that make up stars, gas, planets, and people. We don't yet know what these particles are. Many experiments have been searching for these particles; detecting and understanding their nature is one of the most important open quests in science. When asked what she thought of a theoretical suggestion that dark matter may not exist but instead a change in Newton's gravity law was needed, Vera was open minded: "I don't know if we have dark matter or need a change in gravity or need

[a]Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

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[1]Email: neta@astro.princeton.edu.

something else; we know so little about our universe. It is a strange and mysterious universe. But that's fun."

Vera was born in Philadelphia in 1928; her family moved to Washington, DC when she was 10. Vera was fascinated by astronomy from an early age, watching the stars wheel past her bedroom window or wondering why the Moon always followed her wherever she traveled. She graduated from Vassar College in 1948, continued to Cornell for her Masters in astronomy, then received a doctorate from Georgetown University in 1954, working with the famous physicist George Gamow. Vera's thesis showed that the distribution of galaxies in the universe was clumped rather than uniformly distributed in space, a surprising and important result. Vera joined Carnegie's Department of Terrestrial Magnetism in Washington, DC, in 1965. There she carried out her groundbreaking research with Kent Ford and meticulously mentored generations of young scientists studying galaxy dynamics and dark matter.

Early challenges as a woman in science never deterred Vera. She tells her personal story in a nice autobiographical article (5). A college interviewer, who dismissed her interest in doing research in astronomy, asked if Vera would consider instead a career painting astronomical objects (I can only guess her reply. . .). A department chair suggested that he should present her research paper at an upcoming American Astronomical Society conference, instead of her, because she was pregnant. Replied young Vera: "That's OK; I'll do it." She was denied observing on the Hale telescope at Palomar because women were not allowed until the 1960s. "Don't let anyone keep you down for silly reasons" she liked to say. Vera passionately supported women scientists, always encouraging, inspiring, helping pave their way, saying "worldwide, half of all brains are in women," and "there is no problem in science that can be solved by a man that cannot be solved by a woman."

Cheerful, enthusiastic, and positive, Vera was a kind, caring, and fun-loving person. She had a loving family, consisting of her husband Bob Rubin, also a scientist, and four wonderful children, all scientists themselves.

Vera's seminal accomplishments have been honored by numerous awards, including the US National Medal of Science, the Gold Medal of the Royal Astronomical Society, the Gruber Cosmology Prize, the Watson Medal of the National Academy of Sciences, and many honorary degrees. The Nobel missed their opportunity to recognize Vera's vital observations, as they missed other important ones. Vera's legacy as the "mother" of flat rotation curves and dark matter will be forever honored, as will her legacy as a mentor and role model of generations of scientists, men and women. Through these generations, her star will continue to shine.

1 Rubin VC, Ford WK, Jr (1970) Rotation of the Andromeda nebula from a spectroscopic survey of emission regions. *Astrophys J* 159:379–403.

2 Roberts MS (1966) A high-resolution 21-CM hydrogen-line survey of the Andromeda nebula. *Astrophys J* 144:639–656.

3 Roberts MS, Rots AH (1973) Comparison of rotation curves of different galaxy types. *Astron Astrophys* 26:483–485.

4 Rubin VC, Ford WK, Jr, Thonnard N (1978) Extended rotation curves of high-luminosity spiral galaxies. IV—Systematic dynamical properties, SA through SC. *Astrophys J Lett* 225:L107–L111.

5 Rubin VC (2011) An interesting voyage. *Annu Rev Astron Astrophys* 49:1–28.