Seeing dark matter in the Andromeda galaxy

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Vera Rubin is an observational astronomer who has studied motions of stars and gas in galaxies for 75% of her life. She is at the Department of Terrestrial Magnetism, Carnegie Institution of Washington in Washington, DC.

This is a story of why and how Kent Ford and I studied the orbital velocities of stars in the Andromeda galaxy 40 years ago. Our study was influential in the later conclusion that most of the matter in the universe is dark.

In January 1965 I walked into the Department of Terrestrial Magnetism (affectionately known as DTM), and asked for a job. I had been working at Georgetown University since obtaining my PhD there a decade earlier. But teaching, doing research, and traveling to observatories complicated a busy family life that included a physicist husband and four active children.

It was typical of DTM's unconventional ways that I was not handed a job application. Instead, I was handed a new 2 in. × 2 in. glass plate containing a spectrum of a star, and asked if I could measure its velocity. Back at Georgetown I measured it, and I got the job.

Kent Ford, a DTM physicist, had recently built an image tube spectrograph. It incorporated a two-stage magnetically focused RCA cascaded image tube at the focus of a Cassegrain Schmidt camera. Baked II-aO plates photographed the image tube's final phosphor screen. Using this device on a telescope reduced the exposure time to 1/10th that of an unaided photographic plate. It was a major step forward in telescope instrumentation.

The next year Kent and I embarked on a program to measure rotation velocities in the Andromeda galaxy, M31. We hoped to determine the rotation curve—the velocity relative to the M31 nucleus as a function of nuclear distance—as far out as possible, and thus deduce M31's mass. In our solar system, the orbital velocity of each planet is determined by its distance from the Sun. In a disk galaxy, the disk stars all orbit in the same direction; each star's velocity is determined by the total mass interior to its orbit.

In M31 we hoped to detect the Hα spectral line emitted by hydrogen gas clouds that had been ionized by nearby hot stars. Spectral lines shift blueward (redward) as the star's orbit carries it toward (away from) the observer. I had long been interested in orbital motions of stars at the outer parts of galaxies, a subject little studied. Kent was interested in using the spectrograph at the limits of its capabilities.

It was not simple to work at Lowell Observatory in the 1960s. I would arrive several days before the allotted nights to cut photographic plates into 2 in. × 2 in. squares in total darkness. Baking a plate in an oven for 72 hours magically increased its sensitivity. At the telescope, Kent and I would each guide an exposure in turn, making tiny adjustments to the telescope to keep the guide star exactly on the cross wires. I thought I guided best, and would not relinquish my turn; Kent behaved the same way. We worked in almost total darkness, for a light leak in the telescope or spectrograph could ruin the exposure. I developed the plates.

At the telescope

In December 1967 we took our first spectrum. It was one of 688 Hα regions in M31 that Carnegie astronomer Walter Baade photographed and identified[1] in the 1940s, using the Mt. Wilson 100-in. telescope. The regions were too faint to be visible at the 72-in. Lowell or the 84-in. Kitt Peak telescopes, so we set the telescope by "blind offsets" using exact distances calculated from bright stars on Baade's charts. We also had to account for any slight rotation of the telescope field. A hard task in a cold dark dome with freezing fingers inside heavy gloves.

After completing our first 70-minute exposure, Kent and I and a visiting astronomer (observers love to visit other observers at a telescope) went to the darkroom. I developed the plate and turned on the lights while the plate was washing. We were excited to see a lovely spectrum, and knew then that the program could succeed. Our guest offered to finish the washing so we could start offsetting for the next re-

gion. In a few minutes he returned to the dome, leaving the plate washing in running water. When we returned to the darkroom after the next exposure, we found a clear 2 in. × 2 in. piece of glass washing in a basin of hot water! Our guest had mistakenly washed the plate in hot water, causing the emulsion to slither off. Our logbook reads: PLATE DESTROYED IN WASHING. But it didn't matter. I was euphoric! We had proved that we could measure velocities of individual regions in M31, 2.5 million light years from our telescope.

During 1968 and 1969, we observed M31 at Lowell and Kitt Peak whenever we had telescope time. To observe at Kitt Peak, we loaded a van with the spectrograph, power supply, tools, boxes for plate baking, and log books, and drove 300 miles from Flagstaff to Kitt Peak.

Once, the crane in the Lowell dome failed, so Kent and I carried the heavy spectrograph down the dome stairs and headed for Kitt Peak. Dirt roads on arid Native American lands were a visual contrast to the Japanese flower farms south of Phoenix. At the observatory loading dock, three or four Tohono O'odham Native American workmen helped us unload. I never knew if their comment, "There must be an easier way to make a living," referred to them or to us.

Regulations required that a telescope operator stay at the 84-in. telescope all night. Operators hated our arrival, for after setting the telescope on M31 at the twilight start, they had no duties until dawn. They even covered the luminous clock dial, knowing that I objected to any lights. Standing at the telescope in a black dome during a many-hour exposure, guiding by a nearby star, I found the greenish glow of the M31 nucleus exhilarating and a little spooky. Often I wondered if an astronomer in M31 was observing us. Always I wished we could exchange views.

From 1967 to 1969, Kent and I obtained spectra and derived orbital velocities for 67 regions whose distances from M31's center range out to 120 arcmin (8 900 light years), the farthest region
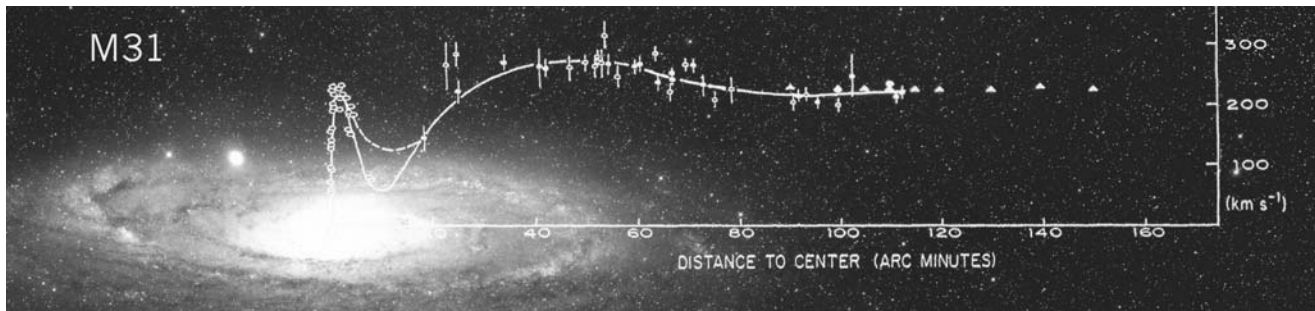
The M31 major axis mean optical radial velocities and the rotation curve,[4] r < 120 arcmin, superposed on the M31 image from the Palomar Sky Survey. Velocities from radio observations[5] are indicated by triangles, 90 < r < 150 arcmin. Rotation velocities remain flat well beyond the optical galaxy, implying that the M31 cumulative mass rises linearly with radius. (Image by Rubin and Janice Dunlap.)

identified by Baade. Interior to 16 arcmin, no regions were found, so we used a long spectrograph slit placed across the M31 nucleus, and detected and measured a weak nitrogen emission line. Exposures ranged from one to several hours. During the long exposures, I would flash my faint red light periodically to identify my surroundings. After our observing run, we carried the plates to DTM. Kent, the consummate instrumentalist, constructed an aluminum can to carry wet plates developed the last night. At DTM, I measured the spectra on a two-dimensional measuring microscope, punched cards manually, and calculated velocities using an early IBM computer.

In my talk at the American Astronomical Society meeting in Austin, Texas, in December 1968, I showed our preliminary rotation curve for M31. The result attracted attention because it represented the largest extent of an optical galaxy rotation curve.[2] Earlier attempts to derive extended rotation curves for galaxies failed[3] because spectrographs were not stable over the tens of hours (3 months for M31 in 1917) for a single exposure. Even spectra obtained by others in the 1960s failed to yield velocities beyond the visibly bright galaxy.

After my talk, the esteemed Rudolph Minkowski asked when we would publish the paper. I replied, "There are hundreds more regions that we could observe." He looked at me sternly and said, emphatically, "I think you should publish the paper now." We did.

'Tis a puzzlement

Our 1970 paper included optical observations out to 120 arcmin[4] but did not include the superposed image of M31, or the 1975 radio observations[5] shown in the figure. This composite of the galaxy and velocities emphasizes the extent of the optical image and the "flatness" of the velocities. We found it puz-

zling that stars far from the center traveled as fast as those much closer to the center. However, we chose not to extend the curve beyond the final measurement by using a decreasing Newtonian inverse square velocity, the common practice at that time. Instead, we wrote "extrapolation beyond that point is clearly a matter of taste."

Isaac Newton showed that the force on a mass at radius r from the center of a symmetrical mass distribution is proportional to the mass interior to that r. High-school students learn that in a gravitationally bound system like our solar system, a planet moves in a closed orbit, such that $MG = V^2r$ where M is the mass of the Sun, G is the gravitational constant, and V and r are the velocity of a planet and its distance from the Sun. In M31, the same relation between mass, velocity, and distance holds. A flat rotation curve (V = constant) implies that mass increases linearly with distance from the center. (I leave this as an exercise for the reader.) Enormous amounts of nonluminous matter extend far beyond the optical image of M31.

Although in the 1930s Fritz Zwicky and Sinclair Smith had suggested that dark matter stabilizes clusters of galaxies,[6] their ideas were largely ignored. Our M31 study offered new evidence for dark matter in the universe. After our 1970 paper, it would take a decade of more observations of flat rotation curves and brilliant theoretical ideas[7] for the scientific community to embrace the concept that most matter in the universe is dark.[8]

Early on, I had discussed M31 with Mort Roberts, a near neighbor at the National Radio Astronomy Observatory in Charlottesville, Virginia. In 1975 Roberts and Robert Whitehurst published their survey of the southern end of M31, observed with the 300-ft. Green Bank radio telescope.[5] They traced the

extent and velocity of neutral hydrogen gas, using the 21-cm hyperfine transition (a spin flip in the H atom). To the limits of their detection, 150 arcmin, the velocities remain flat. It was Mort who first showed me a superposition of the M31 velocities and the optical image. That composite is a wonderful illustration of the concept of dark matter. The figure raises the questions: What's spinning the stars and gas around so fast beyond the optical galaxy? What's keeping them from flying out into space? The current answer is, "Gravity, from matter that has no light."

Now, 40 years after Kent and I started studying M31, astronomers know that more than 90% of the matter in the universe is dark, but we only have theories about its composition. The simplicity of our M31 optical observing contrasts with the sophistication of current dark-matter galaxy models and with the experiments planned by particle physicists. A few brave, smart cosmologists work to modify Newton's laws to account for the observations. But no one can predict the surprises that surely lie ahead as we attempt to shed light on nature's dark secret.

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