Section 2: *Initial Evidence of Dark Matter*

Fritz Zwicky, an astronomer at the California Institute of Technology, stumbled across the gravitational effects of dark matter in the early 1930s while studying how galaxies move within the Coma Cluster. The Coma Cluster consists of approximately 1,000 galaxies spread over about two degrees on the sky—roughly the size of your thumb held at arm's length, and four times the size of the Sun and the Moon seen from Earth. Gravity binds the galaxies together into a cluster, known as a galaxy cluster. Unlike the gravitationally bound planets in our solar system, however, the galaxies do not orbit a central heavy object like the Sun and thus execute more complicated orbits.

To carry out his observations, Zwicky persuaded Caltech to build an 18-inch Schmidt telescope that could capture large numbers of galaxies in a single wide-angle photograph. He used the instrument to make a survey of all the galaxies in the cluster and used measurements of the Doppler shift of their spectra to determine their velocities. He then applied the virial theorem. A straightforward application of classical mechanics, the virial theorem relates the velocity of orbiting objects to the amount of gravitational force acting on them. Isaac Newton's theory tells us that gravitational force is proportional to the masses of the objects involved, so Zwicky was able to calculate the total mass of the Coma Cluster from his measured galactic velocities.

See the math

Figure 4: The Coma Cluster, which provided the first evidence for dark matter.
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Zwicky also measured the total light output of all the cluster's galaxies, which contain about a trillion stars altogether. When he compared the ratio of the total light output to the mass of the

THE FATHER OF DARK MATTER—AND MORE

Fritz Zwicky. © AIP Emilio Segrè Visual Archives, Physics Today Collection.

A Swiss national, Fritz Zwicky found his scientific home at the California Institute of Technology. From his perch on Caltech's Mount Wilson Observatory, Zwicky discovered more of the exploding stars known as "supernovae" than all his predecessors combined. But astrophysicists today admire him mostly for his theoretical insights into such phenomena as neutron stars, gravitational lenses, and—perhaps most important of all—dark matter.

Zwicky's observations of supernovae in distant galaxies laid the foundation of his theoretical work. As he detected supernovae in ever-more distant

Coma Cluster with a similar ratio for the nearby Kapteyn stellar system, he found the light output per unit mass for the cluster fell short of that from a single Kapteyn star by a factor of over 100. He reasoned that the Coma Cluster must contain a large amount of matter not accounted for by the light of the stars. He called it "dark matter."

galaxies, he realized that most galaxies combined in clusters. Careful measurements of the light from clusters led him to suggest the existence of dark matter. That may represent his greatest legacy, but he made other key contributions to astrophysics. He predicted that galaxies could act as gravitational lenses, an effect first observed in 1979, five years after his death. And he and his colleague Walter Baade predicted the transition of ordinary stars into neutron stars, first observed in 1967.

Zwicky's measurements took place just after astronomers had realized that galaxies are very large groups of stars. It took some time for dark matter to become the subject of active research it is today. When Zwicky first observed the Coma Cluster, tests of Einstein's theory were just starting, the first cosmological measurements were taking place, and nuclear physicists were only beginning to develop the theories that would explain the Big Bang and supernovae. Since galaxies are complex, distant objects, it is not surprising that astronomers did not immediately begin to worry about "the dark matter problem."

By the early 1970s, technology, astronomy, and particle physics had advanced enough that the dark matter problem seemed more tractable. General relativity and nuclear physics had come together in the Big Bang theory of the early universe, and the detection of microwave photons from the time when the first atoms formed from free electrons and protons had put the theory on a solid footing. Larger telescopes and more precise and more sensitive light detectors made astronomical measurements quicker and better. Just as important, the emergence of affordable mini-computers allowed physics and astronomy departments to purchase their own high-performance computers for dedicated astronomical calculations. Every advance set the scene for a comprehensive study of dark matter, and two very important studies of dark matter soon appeared.

Dark matter appears in galactic simulations

In 1973, Princeton University astronomers Jeremiah Ostriker and James Peebles used numerical simulation to study how galaxies evolve. Applying a technique called N-body simulation, they programmed 300 mass points into their computer to represent groups of stars in a galaxy rotating about a central point. Their simulated galaxy had more mass points, or stars, toward the center and fewer toward the edge. The simulation started by computing the gravitational force between each pair of mass points from Newton's law and working out how the mass points would move in a small interval of time. By repeating this calculation many times, Ostriker and Peebles were able to track the motion of all the mass points in the galaxy over a long period of time.

Figure 5: James Peebles (left) and Jeremiah Ostriker (right) found evidence for dark matter in their computer simulations.
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For a galaxy the size of the Milky Way (4×10^{20} meters), a mass point about halfway out the edge moves at about 200 kilometers per second and orbits the center in about 50 million years. Ostriker and Peebles found that in a time less than an orbital period, most of the mass points would collapse to a bar-shaped, dense concentration close to the center of the galaxy with only a few mass points at larger radii. This looked nothing like the elegant spiral or elliptical shapes we are used to seeing. However, if they added a static, uniform distribution of mass three to 10 times the size of the total mass of the mass points, they found a more recognizable structure would emerge. Ostriker and Peebles had solid numerical evidence that dark matter was necessary to form the types of galaxies we observe in our universe.

Fresh evidence from the Andromeda galaxy

At about the same time, astronomers Kent Ford and Vera Cooper Rubin at the Carnegie Institution of Washington began a detailed study of the motion of stars in the nearby galaxy of Andromeda. Galaxies are so large that even stars traveling at 200 kilometers per second appear stationary; astronomers must measure their Doppler shifts to obtain their velocities. However, early measurements of stellar velocities in different portions of Andromeda proved very difficult. Since the spectrometers used to measure the shift in frequency took a long time to accumulate enough light, observations of a given portion of Andromeda required several hours or even several nights of observing. Combining images from several observations was difficult and introduced errors into the measurement. However, new and more sensitive photon detectors developed in the early 1970s allowed much shorter measurement times and enabled measurements further out from the center of the galaxy.

Rubin and Ford measured the velocity of hydrogen gas clouds in and near the Andromeda galaxy using the new detectors. These hydrogen clouds orbit the galaxy much as stars orbit within the galaxy. Rubin and Ford expected to find that the hydrogen gas outside the visible edge of the galaxy would be moving slower than gas at the edge of the galaxy. This is what the virial theorem predicts if the mass in the galaxy is concentrated where the galaxy emits light. Instead, they found the opposite: the orbital velocity of the hydrogen clouds remained constant outside the visible edge of the galaxy. If the virial theorem is to be believed, there must be additional *dark* matter outside the visible edge of the galaxy. If Andromeda obeyed Newton's laws, Rubin reasoned, the galaxy must contain dark matter, in quantities that increased with increasing distance from the galactic center.

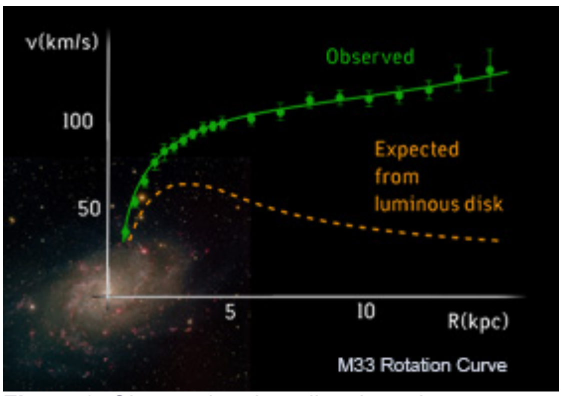

Figure 6: Observed and predicted rotation curves for the galaxy M33, also known as the "Triangulum

FROM CONTROVERSY TO CREDIBILITY

Vera Cooper Rubin at the Lowell Observatory. Kent Ford has his back to us. © Bob Rubin.

Vera Cooper Rubin faced several obstacles on her way to a career in astronomy. A high school physics teacher tried to steer her away from science. A college admissions officer suggested that she avoid majoring in astronomy. Princeton University did not grant her request for a graduate

Galaxy."
Source: © M33 Image: NOAO, AURA, NSF, T. A. Rector. More info

Alternative explanations of the Andromeda observations soon emerged. Theories of Modified Newtonian Dynamics (MOND), for example, aimed to explain the findings by modifying the gravitational interaction over galactic and larger distances. At very low accelerations, which correspond to galactic distances, the theories posit that the gravitational force varies inversely with the distance alone rather than the square of the distance. However, MOND would overturn Einstein's theory in an incredible way: General relativity is based on the simple idea of the equivalence principle. This states that there is no difference between gravitational mass (the mass that causes the gravitational force) and inertial mass (the mass that resists acceleration). There is no fundamental reason to expect these two masses to be the same, nor is there any reason to expect them to be different. But their equivalence forms the cornerstone of Einstein's general theory. MOND theories break that equivalence because they modify either gravity or inertia. If MOND were correct, a fundamental assumption underlying all of modern physics would be false.

catalogue in 1948, because its graduate astronomy program did not accept women until 27 years later. Senior astronomers took a scornful view of her first paper, presented in 1950, on galactic motions independent of the classic expansion of the universe. And when she and collaborator Kent Ford expanded that research in the 1970s, they met so much dissent that they shifted to another field.

The shift proved providential. Rubin and Ford measured the rotational velocities of interstellar matter in orbit around the center of the nearby Andromeda galaxy. Their readings, confirmed by observations on other galaxies, led them to infer that the galaxies must contain dark matter. Confirmation of that fact sealed Rubin's reputation as an astronomer.