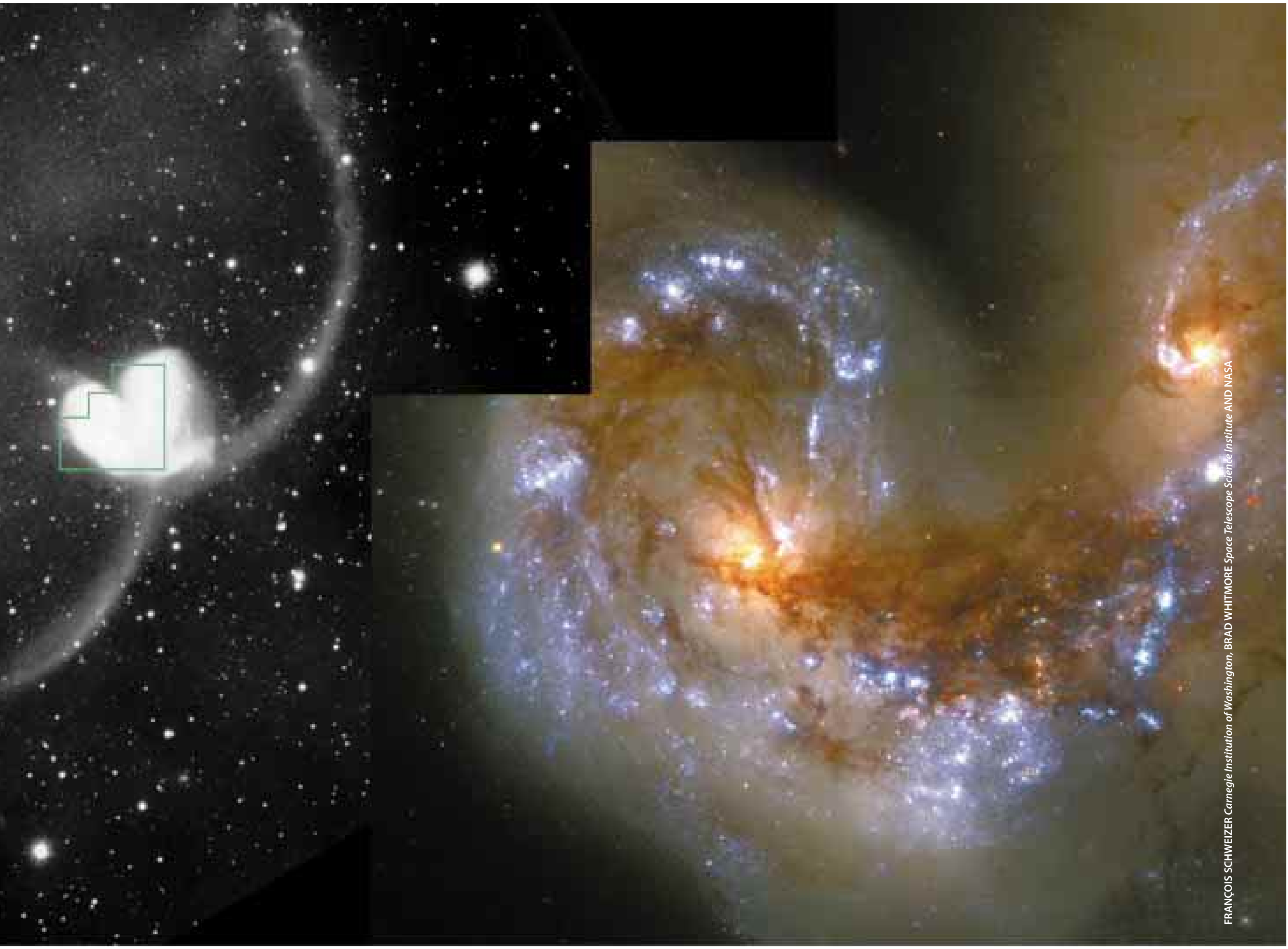
Dark Matter in the Universe

by Vera Rubin



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As much as 90 percent of the matter in the universe is invisible. Detecting this dark matter will help astronomers better comprehend the universe's destiny

Imagine, for a moment, that one night you awaken abruptly from a dream. Coming to consciousness, blinking your eyes against the blackness, you find that, inexplicably, you are standing alone in a vast, pitch-black cavern. Befuddled by this predicament, you wonder: Where am I? What is this space? What are its dimensions?

Groping in the darkness, you stumble upon a book of damp matches. You strike one; it quickly flares, then fizzles out. Again, you try; again, a flash and fizzle. But in that moment, you realize that you can glimpse a bit of your surroundings. The next match strike lets you sense faint walls far away. Another flare reveals a strange shadow, suggesting the presence of a big object. Yet another suggests you are moving—or, instead, the room is moving relative to you. With each momentary flare, a bit more is learned.

In some sense, this situation recalls our puzzling predicament on Earth. Today, as we have done for centuries, we gaze into the night sky from our planetary platform and wonder where we are in this cavernous cosmos. Flecks of light provide some clues about great objects in space. And what we do discern about their motions and apparent shadows tells us that there is much more that we cannot yet see.

From every photon we collect from the universe's farthest reaches, we struggle to extract information. Astronomy is the study of light that reaches Earth from the heavens. Our task is not only to collect as much light as possible—from ground- and space-based telescopes—but also to use what we can see in the heavens to understand better what we cannot see and yet know must be there.

Based on 50 years of accumulated observations of the motions of galaxies and the expansion of the universe, most astronomers believe that as much as 90 percent of the stuff constituting the universe may be objects or particles that cannot be seen. In other words, most of the universe's matter does not radiate—it provides no glow that we can detect in the electromagnetic spectrum. First posited some 60 years ago by astronomer Fritz Zwicky, this so-called missing matter was believed to reside within clusters of galaxies. Nowadays we prefer to call the missing mass "dark matter," for it is the light, not the matter, that is missing.

Astronomers and physicists offer a variety of explanations for this dark matter. On the one hand, it could merely be ordinary material, such as ultrafaint stars, large or small black holes, cold gas, or dust scattered around the universe—all of which emit or reflect too little radiation for our instruments to detect. It could even be a category of dark objects called MACHOs (MAssive Compact Halo Objects) that lurk invisibly in the halos surrounding galaxies and galactic clusters. On the other hand, dark matter could consist of exotic, unfamiliar particles that we have not figured out how to observe. Physicists theorize about the existence of these particles, although experiments have not yet confirmed their presence. A third possibility is that our understanding of gravity needs a major revision—but most physicists do not consider that option seriously.

In some sense, our ignorance about dark matter's properties has become inextricably tangled up with other outstanding issues in cosmology—such as how much mass the universe contains, how galaxies formed and whether or not the universe will expand forever. So important is this dark matter to our understanding of the size, shape and ultimate fate of the universe that the search for it will very likely dominate astronomy for the next few decades.

GALAXIES COLLIDE IN THIS MERGER OF THE ANTENNAE GALAXIES, known as NGC 4038/39, setting off stellar fireworks and yielding more than 1,000 bright new star clusters. The galaxies garnered their name from their long, luminous tails—formed by gravitational tidal forces of their encounter—which resemble insect antennae. Visible in the Southern Hemisphere, the galaxies are 63 million light-years from Earth. This figure (*opposite page*) blends two images: the wide angle (*left*) comes from a ground-based telescope in Chile, whereas the detailed view (*right*) comes from the Hubble Space Telescope.

Observing the Invisible

Understanding something you cannot see is difficult—but not impossible. Not surprisingly, astronomers currently study dark matter by its effects on the bright matter that we do observe. For instance, when we watch a nearby star wobbling predictably, we infer from calculations that a "dark planet" orbits around it. Applying similar principles to spiral galaxies, we infer dark matter's presence because it accounts for the otherwise inexplicable motions of stars within those galaxies.

When we observe the orbits of stars and clouds of gas as they circle the centers of spiral galaxies, we find that they move too quickly. These unexpectedly high velocities signal the gravitational tug exerted by something more than that galaxy's visible matter. From detailed velocity measurements, we conclude that large amounts of invisible matter exert the gravitational force that is holding these stars and gas clouds in high-speed orbits. We deduce that dark matter is spread out around the galaxy, reaching beyond the visible galactic edge and bulging above and below the otherwise flattened, luminous galactic disk. As a rough approximation, try to envision a typical spiral galaxy, such as our Milky Way, as a relatively flat, glowing disk embedded in a spherical halo of invisible material—almost like an extremely diffuse cloud.

Looking at a single galaxy, astronomers see within the galaxy's radius (a distance of about 50,000 light-years) only about one tenth of the total gravitating mass needed to account for how fast individual stars are rotating around the galactic hub.

In trying to discover the amount and distribution of dark matter in a cluster of galaxies, x-ray astronomers have found that galaxies within clusters float immersed in highly diffuse clouds of 100-million-degree gas—gas that is rich in energy yet difficult to detect. Observers have learned to use the x-ray-emitting gas's temperature and extent in much the same way that optical astronomers use the velocities of stars in a single galaxy. In both cases, the data provide clues to the nature and location of the unseen matter.

In a cluster of galaxies, the extent of the x-ray-emitting region and temperature of the gas enable us to estimate the amount of gravitating mass within the cluster's radius, which measures almost 100 million light-years. In a typical case, when we add together the luminous matter and the x-ray-emitting hot gas, we are able to sense roughly 20 to 30 percent of the cluster's total gravitating mass. The remainder, which is dark matter, remains undetected by present instruments.

Subtler ways to detect invisible matter have recently emerged. One clever method involves spotting rings or arcs around clusters of galaxies. These "Einstein rings" arise from an effect known as gravitational lensing, which occurs when gravity from a massive object bends light passing by. For instance,

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LARGE MAGELLANIC CLOUD, one of the Milky Way's nearest satellite galaxies, is located 180,000 light-years from Earth. Like other small satellite galaxies, the cloud will ultimately merge with the Milky Way, thus becoming one of the galaxy's building blocks. As we view the cloud from Earth, dark objects in the Milky Way's halo gravitationally lens some stars in the cloud, thus providing information about the presence of dark matter in our galaxy's halo.

when a cluster of galaxies blocks our view of another galaxy behind it, the cluster's gravity warps the more distant galaxy's light, creating rings or arcs, depending on the geometry involved. Interestingly, the nearer cluster acts as nature's telescope, bending light into our detectors—light that would otherwise have traveled elsewhere in the universe. Someday we may exploit these natural telescopes to view the universe's most distant objects.

Using computer models, we can calculate the mass of the intervening cluster, estimating the amount of invisible matter that must be present to produce the observed geometric deflection. Such calculations confirm that clusters contain far more mass than the luminous matter suggests.

Even compact dark objects in our own galaxy can gravitationally lens light. When a foreground object eclipses a background star, the light from the background star is distorted into a tiny ring, whose brightness far exceeds the star's usual brightness. Consequently, we observe an increase, then a decrease, in the background star's brightness. Careful analysis of the light's variations can tease out the mass of the dark foreground lensing object.

Where Is Dark Matter?

Several teams search nightly for nearby lensing events, caused by invisible MACHOs in our own Milky Way's halo. The search for them covers millions of stars in the Magellanic Clouds and the Andromeda galaxy. Ultimately, the search will limit the amount of dark matter present in our galaxy's halo.

Given the strong evidence that spiral and elliptical galaxies lie embedded in large dark-matter halos, astronomers now wonder about the location, amount and distribution of the invisible material.

To answer those questions, researchers compare and contrast observations from specific nearby galaxies. For instance, we learn from the motions of the Magellanic Clouds, two satellite galaxies gloriously visible in the Southern Hemisphere, that they orbit within the Milky Way galaxy's halo and that the halo continues beyond the clouds, spanning a distance of almost 300,000 light-years. In fact, motions of our galaxy's most distant satellite objects suggest that its halo may extend twice as far—to 600,000 light-years.

Because our nearest neighboring spiral galaxy, Andromeda, lies a mere two million light-years away, we now realize that our galaxy's halo may indeed span a significant fraction of the distance to Andromeda and its halo. We have also determined that clusters of galaxies lie embedded in even larger systems of dark matter. At the farthest distances for which we can deduce the masses of galaxies, dark matter appears to dwarf luminous matter by a factor of at least 10, possibly as much as 100.

Overall, we believe dark matter associates loosely with bright matter, because the two often appear together. Yet, admittedly, this conclusion may stem from biased observations, because bright matter typically enables us to find dark matter.

By meticulously studying the shapes and motions of galaxies over decades, astronomers have realized that individual galaxies are actively evolving, largely because of the mutual gravitational pull of galactic neighbors. Within individual galaxies, stars remain enormously far apart relative to their diameters, thus little affecting one another gravitationally. For example, the separation between the sun and its nearest neighbor, Proxima Centauri, is so great that 30 million suns could fit between the two. In contrast, galaxies lie close together, relative to their diameters—nearly all have neighbors within a few diameters. So galaxies do alter one another gravitationally, with dark matter's added gravity a major contributor to these interactions.

As we watch many galaxies—some growing, shrinking, transforming or colliding—we realize that these galactic motions would be inexplicable without taking dark matter into account. Right in our own galactic neighborhood, for instance, such interactions are under way. The Magellanic Clouds, our second nearest neighboring galaxies, pass through our galaxy's plane every billion years. As they do, they mark their paths with tidal tails of gas and, possibly, stars. Indeed, on every passage, they lose energy and spiral inward. In less than 10 billion years, they will fragment and merge into the Milky Way.

Recently astronomers identified a still nearer neighboring galaxy, the Sagittarius dwarf, which lies on the far side of the Milky Way, close to its outer edge. (Viewed from Earth, this dwarf galaxy appears in the constellation Sagittarius.) As it turns out, gravity from our galaxy is pulling apart this dwarf galaxy, which will cease to exist as a separate entity after several orbits. Our galaxy itself may be made up of dozens of such previous acquisitions.

Similarly, the nearby galaxy M31 and the Milky Way are now hurtling toward each other at the brisk clip of 130 kilometers (81 miles) per second. As eager spectators, we must watch this encounter for a few decades to know if M31 will strike our galaxy or merely slide by. If they do collide, we will lose: the Milky Way will merge into the more massive M31. Computer models predict that in about four billion years the galactic pair will become one spheroidal galaxy. Of course, by then our sun will have burned out—so others in the universe will have to enjoy the pyrotechnics.

In many ways, our galaxy, like all large galaxies, behaves as no gentle neighbor. It gobbles up nearby companions and grinds them into building blocks for its own growth. Just as Earth's continents slide beneath our feet, so, too, does our galaxy evolve around us. By studying the spinning, twisting and turning motions and structures of many galaxies as they hurtle through space, astronomers can figure out the gravitational forces required to sustain their motions—and the amount of invisible matter they must contain.

How much dark matter does the universe contain? The destiny of the universe hinges on one still unknown parameter: the total mass of the universe. If we live in a high-density, or "closed," universe, then mutual gravitational attraction will ultimately halt the universe's expansion, causing it to contract—culminating in a big crunch, followed perhaps by reexpansion. If, on the other hand, we live in a low-density, or "open," universe, then the universe will expand forever.

Observations thus far suggest that the universe—or, at least, the region we can observe—is open, forever expanding. When we add up all the luminous matter we can detect, plus all the dark matter that we infer from observations, the total still comes to only a fraction—perhaps 20 percent—of the density needed to stop the universe from expanding forever.

I would be content to end the story there, except that cosmologists often dream of, and model, a universe with "critical" density—meaning one that is finely balanced between high and low density. In such a universe, the density is just right. There is enough matter to slow the universe's continuous expansion, so that it eventually coasts nearly to a halt. Yet this model does not describe the universe we actually measure. As an observer, I recognize that more matter may someday be detected, but this does not present sufficient reason for me to adopt a cosmological model that observations do not yet require.

Another complicating factor to take into account is that totally dark systems may exist—that is, there may be agglomerations of dark matter into which luminous matter has never penetrated. At present, we simply do not know if such totally dark systems exist because we have no observational data either to confirm or to deny their presence.

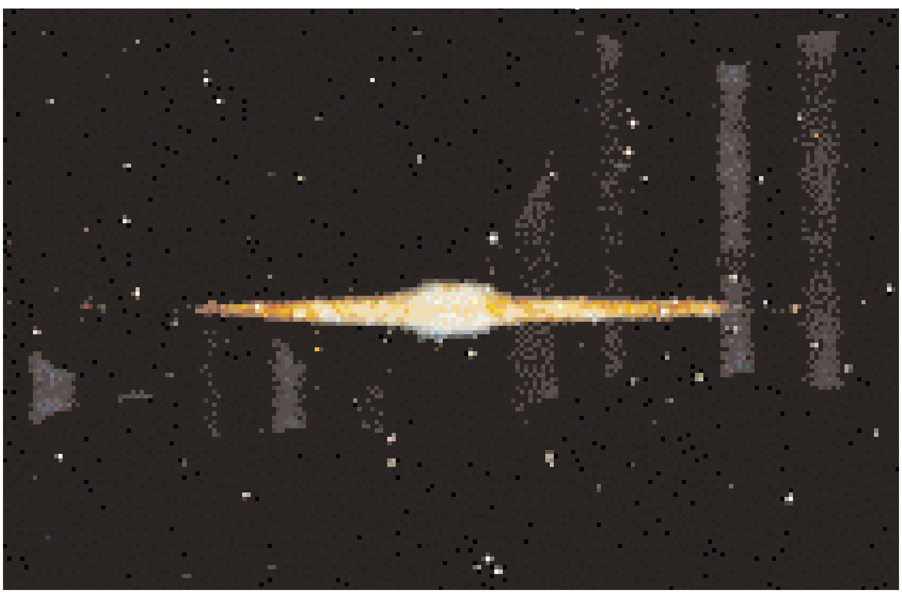
What Is Dark Matter?

Whatever dark matter turns out to be, we know for certain that the universe contains large amounts of it. For every gram of glowing material we can detect, there may be tens of grams of dark matter out there. Currently the astronomical jury is still out as to exactly what constitutes dark matter. In fact, one could say we are still at an early stage of exploration. Many candidates exist to account for the invisible mass, some relatively ordinary, others rather exotic.

Nevertheless, there is a framework in which we must work. Nucleosynthesis, which seeks to explain the origin of elements after the big bang, sets a limit to the number of baryons—particles of ordinary, run-of-the-mill matter—that can exist in the universe. This limit arises out of the Standard Model of the early universe, which has one free parameter—the ratio of the number of baryons to the number of photons.

From the temperature of the cosmic microwave background—which has been measured—the number of photons is now known. Therefore, to determine the number of baryons, we must observe stars and galaxies to learn the cosmic abundance of light nuclei, the only elements formed immediately after the big bang.

Without exceeding the limits of nucleosynthesis, we can construct an acceptable model of a low-density, open universe. In that model, we take approximately equal amounts of baryons and exotic matter (nonbaryonic particles), but in quantities that add up to only 20 percent of the matter needed to close the universe. This model universe matches all our actual observations. On the other hand, a slightly different model of an open universe in which all matter is baryonic would also satis-



NASA GODDARD SPACE FLIGHT CENTER; COURTESY OF COBE SCIENCE WORKING GROUP

INSIDER'S VIEW OF OUR GALAXY is shown here by its near-infrared radiation. Data come from the Diffuse Infrared Background Experiment (DIRBE), part of the National Aeronautics and Space Administration's space-based Cosmic Background Explorer (COBE). Viewing the Milky Way (its central bulge and surrounding disk) from within the disk, DIRBE captures the sky's changing brightness, observed at wavelengths 1.2, 2.3 and 3.5 microns (*blue, green and red, respectively*). The sun sits roughly 28,000 light-years from our galaxy's center. Such data help astronomers fathom the Milky Way's large-scale structure and evolution.

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SPIRAL GALAXY NGC 2997, located in the southern Antlia cloud, probably resembles our own galaxy. Like all spiral galaxies, NGC 2997 is embedded in an extended dark diffuse halo, whose composition remains unknown.

fy observations. Unfortunately, this alternative model contains too many baryons, violating the limits of nucleosynthesis. Thus, any acceptable low-density universe has mysterious properties: most of the universe's baryons would remain invisible, their nature unknown, and in most models much of the universe's matter is exotic.

Exotic Particles

Theorists have posited a virtual smorgasbord of objects to account for dark matter, although many of them have fallen prey to observational constraints. As leading possible candidates for baryonic dark matter, there are black holes (large and small), brown dwarfs (stars too cold and faint to radiate), sun-size MACHOs, cold gas, dark galaxies and dark clusters, to name only a few.

The range of particles that could constitute nonbaryonic dark matter is limited only slightly by theorists' imaginations. The particles include photinos, neutrinos, gravitinos, axions and magnetic monopoles, among many others. Of these, researchers have detected only neutrinos—and whether neutrinos have any mass remains unknown. Experiments are under way to detect other exotic particles. If they exist, and if one has a mass in the correct range, then that particle might pervade the universe and constitute dark matter. But these are very large "ifs."

To a great extent, the details of the evolution of galaxies and clusters depend on properties of dark matter. Without knowing those properties, it is difficult to explain how galaxies evolved into the structures observed today. As knowledge of the early universe deepens, I remain optimistic that we will soon know much more about both galaxy formation and dark matter.

What we fail to see with our eyes, or detectors, we can occasionally see with our minds, aided by computer graphics. Computers now play a key role in the search for dark matter. Historically, astronomers have focused on observations; now the field has evolved into an experimental science. Today's astronomical experimenters sit neither at lab benches nor at telescopes but at computer terminals. They scrutinize cosmic simulations in which tens of thousands of points, representing stars, gas and dark matter, interact gravitationally over a galaxy's lifetime. A cosmologist can tweak a simulation by adjusting the parameters of dark matter and then watch what happens as virtual galaxies evolve in isolation or in a more realistic, crowded universe.

Computer models can thus predict galactic behavior. For instance, when two galaxies suffer a close encounter, violently merging or passing briefly in the night, they sometimes spin off long tidal tails. Yet from the models, we now know these tails appear only when the dark matter of each galaxy's halo is three to 10 times greater than its luminous matter. Heavier halos produce stubbier tails. This realization through modeling has helped observational astronomers to interpret what they see and to understand more about the dark matter they cannot see. For the first time in the history of cosmology, computer simulations actually guide observations.

New tools, no less than new ways of thinking, give us insight into the structure of the heavens. Less than 400 years ago Galileo put a small lens at one end of a cardboard tube and a big brain at the other end. In so doing, he learned that the faint stripe across the sky, called the Milky Way, in fact comprised billions of single stars and stellar clusters. Suddenly, a human being understood what a galaxy is. Perhaps in the coming century, another—as yet unborn—big brain will put her eye to a clever new instrument and definitively answer, What is dark matter? SA

The Author

VERA RUBIN is a staff member at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, where she has been since 1965. That same year, she became the first woman permitted to observe at Palomar Observatory. The author of more than 200 papers on the structure of the Milky Way, motions within galaxies and large-scale motions in the universe, she received Carnegie Mellon University's Dickson Prize for Science in 1994 and the Royal Astronomical Society's Gold Medal in 1996. President Bill Clinton awarded her the National Medal of Science in 1993 and appointed her to the President's Committee on the National Medal of Science in 1995.