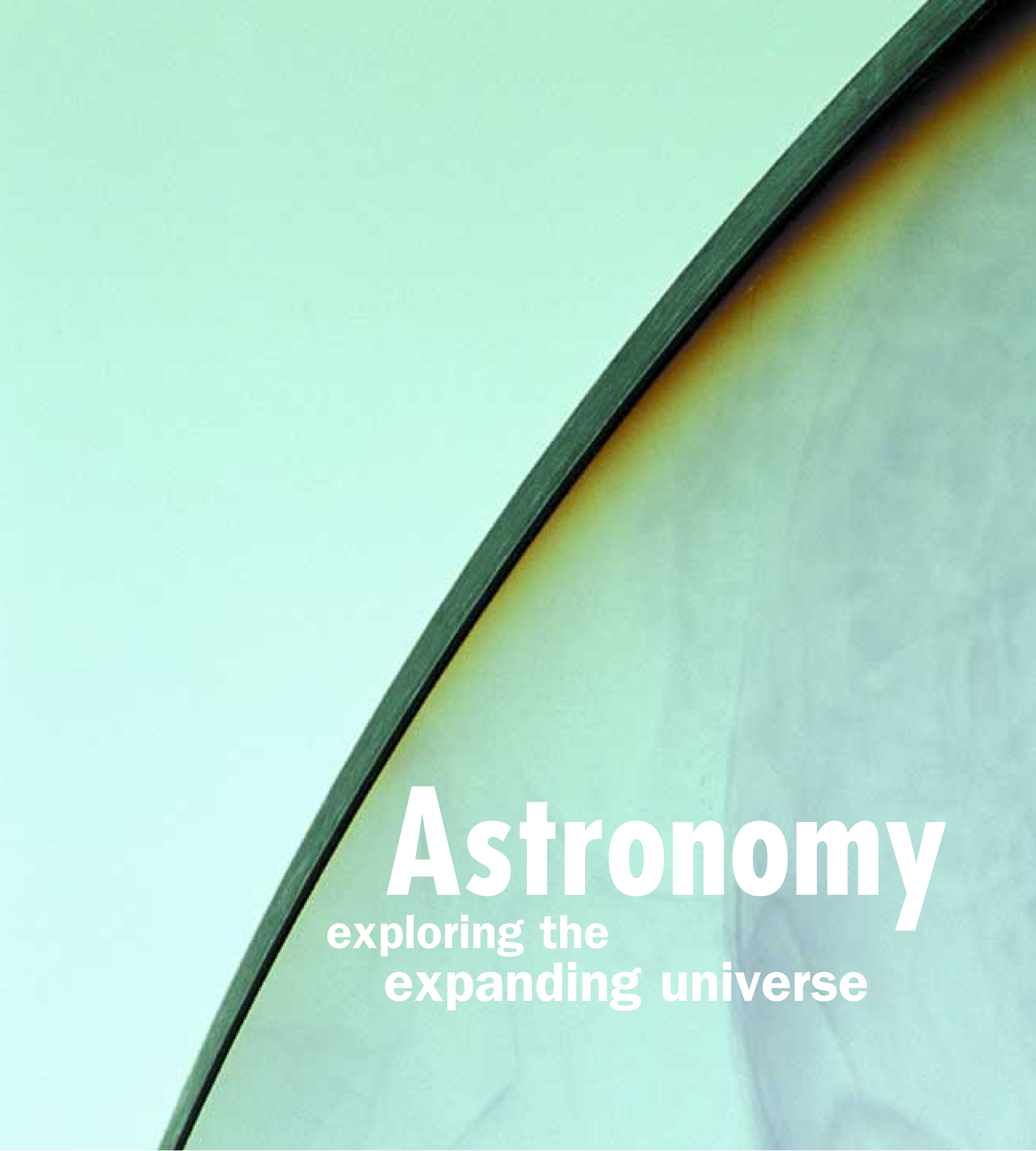
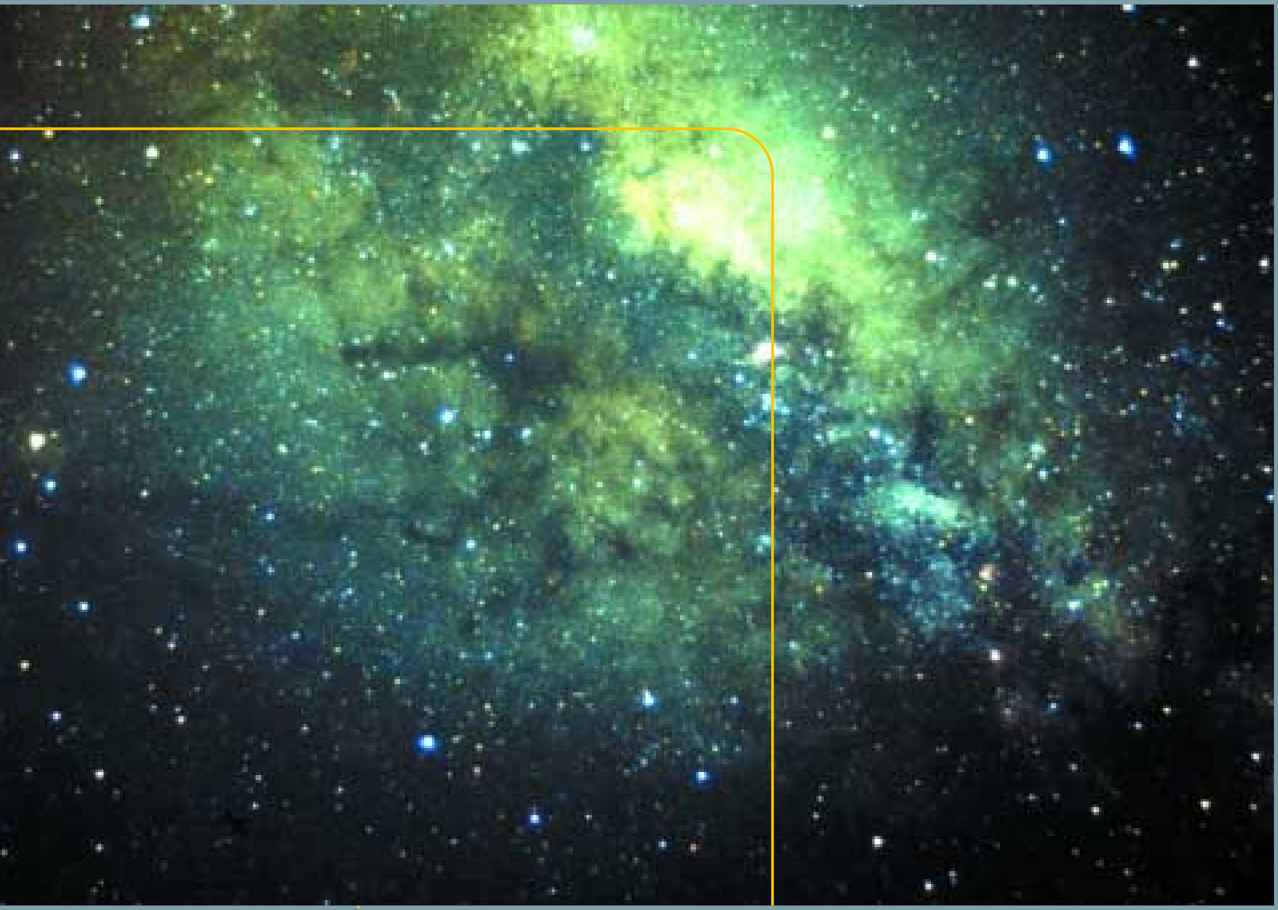


Astronomy

exploring the expanding universe

Using powerful instruments developed with NSF's support, investigators are closing in on fundamental truths about the universe. The work of these scientists creates new knowledge about the Sun, leads to the discovery of planets around distant stars, and uncloaks the majestic subtlety of the universe.



Ever since Galileo perfected the telescope and made the stars seem closer to Earth, scientists have been searching the heavens, asking fundamental questions about the universe and our place in it. Today's astronomers are finding that they don't have to go far for some of the answers. With major funding from NSF, some researchers are exploring the interior of the Sun by recording and studying sound waves generated near its surface. Others are discovering planets around distant stars and expressing optimism about finding still more, some of which may resemble Earth. With sophisticated equipment and techniques, we humans are finally "seeing" what lurks at the center of the Milky Way, hidden from direct view. We are making profound progress in uncovering the origins of the universe, estimating when it all began, and looking at its structure, including the more than 90 percent of its mass known today as "dark matter."

New Visions

"All of a sudden, astronomers have turned a big corner and glimpsed in the dim light of distant lampposts a universe more wondrous than they had previously known," writes John Noble Wilford in the February 9, 1997, issue of the *New York Times.* "Other worlds are no longer the stuff of dreams and philosophic musings. They are out there, beckoning, with the potential to change forever humanity's perspective on its place in the universe."

Wilford is describing research by NSF-funded astronomers Geoffrey W. Marcy and R. Paul Butler of San Francisco State University, who were among the first to discover planets outside our solar system. Wilford's words highlight the excitement and wonder of research in astronomy.

With these and other recent discoveries, astronomers and astrophysicists are taking a fresh look at the realities and mysteries of the universe. Indeed, all of humankind is learning how immense and complex is the space we inhabit. Yet as we start to understand some of the phenomena around us, many other mysteries arise.

NSF is not alone in funding studies of the skies; much work was done before NSF was established in 1950, and universities and other government agencies have done much since then to advance our understanding. But NSF funding—covering such things as state-of-the-art telescopes, supercomputer sites, and individual researchers—is one of the main reasons we have identified so many pieces of the puzzle that is our universe.

So how do researchers get a handle on something so big? Where do they start? For some astronomers, the answer is close to home.

Voyage to the Center of the Sun

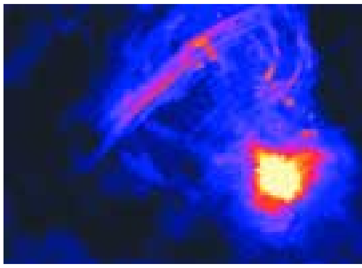
Despite its relative proximity to Earth, the Sun has kept its distance, reluctant to reveal its secrets. Until recently, its inner workings were a mystery of cosmic proportions.

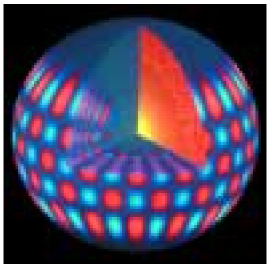
For many years, researchers have known that deep in the Sun's interior, 600 million tons of hydrogen fuse into helium every second, radiating out the resulting energy. And while the mechanics of this conversion have been described in theory, the Sun's interior has remained inaccessible. Now, however, the Sun is being "opened," its internal structures probed, and its inner dynamics surveyed by NSF-supported scientists using investigative techniques—a branch of astronomy known as helioseismology.

"The Sun is the Rosetta stone for understanding other stars," explains John Leibacher, an astronomer at the National Optical Astronomy Observatories in Tucson, Arizona, and director of the NSF-funded Global Oscillation Network Group, or GONG. The Rosetta stone is a tablet with an inscription written in Greek, Egyptian hieroglyphic, and Demonic. The stone's discovery was the key to deciphering ancient Egyptian hieroglyphic and unlocking the secrets of that civilization.

GONG researchers study the Sun by analyzing the sound waves that travel through it. Much as the waves produced by earthquakes and explosions roll through the Earth, these solar sound waves pass through the Sun's gaseous mass and set its surface pulsating like a drumhead. With six telescopes set up around the Earth collecting data every minute, GONG scientists are learning about the Sun's structure, dynamics, and magnetic field by measuring and characterizing these pulsations.

NSF-funded researcher Andrea Ghez has discovered the presence of an enormous black hole at the center of our galaxy. Her work has enormous implications for our understanding of how galaxies evolve.





This computer representation depicts one of nearly ten million modes of sound wave oscillations of the Sun, showing receding regions in red tones and approaching regions in blue. Using the NSF-funded Global Oscillation Network Group (GONG) to measure these oscillations, astronomers are learning about the internal structure and dynamics of our nearest star.

Analysis of data from GONG and other sources shows that current theories about the structure of the Sun need additional work. For example, the convection zone—the region beneath the Sun's surface where pockets of hot matter rise quickly and mix violently with ambient material—is much larger than originally thought. Furthermore, says Leibacher, the zone ends abruptly. "There is turbulent mixing and then quiet. We can locate the discontinuity with great precision." Some research teams are probing deeper and examining the Sun's core; still others are addressing such topics as sunspots—places of depressed temperature on the surface where the Sun's magnetic field is particularly intense.

New insight into the Sun's core came in the spring of 2000, when NSF-funded researchers analyzing GONG data announced that they had discovered a solar "heartbeat." That is, they had found that some layers of gas circulating below the Sun's surface speed up and slow down in a predictable pattern—about every sixteen months. This pattern appears to be connected to the cycle of eruptions seen on the Sun's surface.

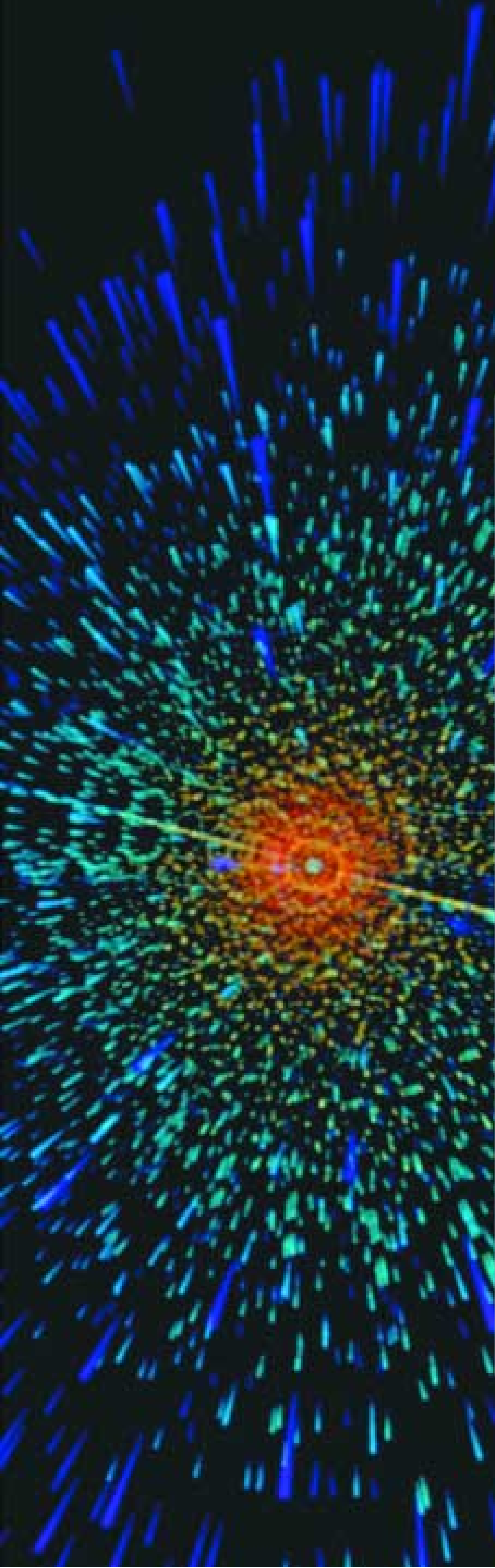
Such eruptions can cause significant disturbances in Earth's own magnetic field, wreaking havoc with telecommunications and satellite systems. A major breakthrough in the ability to forecast these so-called solar storms also came in the spring of 2000, when NSF-funded astrophysicists, using ripples on the Sun's surface to probe its interior, developed a technique to image explosive regions on the far side of the Sun. Such images should provide early warnings of potentially disruptive solar storms before they rotate toward Earth.

As our nearest star, the Sun has always been at the forefront of astrophysics and astronomy. (Astrophysicists study the physics of cosmic objects, while astronomers have a broader job description—they observe and explore all of the universe beyond Earth.) The more we learn about the Sun, the more we understand about the structure and evolution of stars and, by extension, of galaxies and the universe. The Sun also is host to a family of nine planets and myriad asteroids and cometary bodies. As we investigate the richness of outer space, we often look for things that remind us of home.

New Tools, New Discoveries

Much of astronomy involves the search for the barely visible—a category that describes the overwhelming majority of objects in the universe, at least for the time being. One of today's most effective tools for detecting what cannot be seen is Arecibo Observatory in Puerto Rico. The site is one of the world's largest and most powerful telescopes for radar and radio astronomy. Operated by Cornell University under a cooperative agreement with NSF, the Arecibo telescope collects extraterrestrial radio waves of almost imperceptible intensity in a 1,000-foot-wide dish. This telescope, used by scientists from around the world, is a dual-purpose instrument. About three-quarters of the time, the telescope detects, receives, amplifies, and records signals produced by distant astronomical objects. The rest of the time, it measures reflected radio signals that were transmitted by its antenna. The signals bounce off objects such as planets, comets, and asteroids, allowing researchers to determine each object's size and motion.

It was at Arecibo in 1991 that Alexander Wolszczan of Pennsylvania State University discovered the first three planets found outside our solar system. With support from NSF, Wolszczan discovered these planets by timing the radio signals coming from a distant pulsar—a rapidly rotating neutron star—7,000 trillion miles from Earth in the constellation Virgo. He saw small, regular variations in the pulsar's radio signal and interpreted them as a complicated wobble in the pulsar's motion induced by planets orbiting the



Visualizing the Big Picture

While telescopes, spacecraft, and other means of collecting data are critical, not all researchers turn to the heavens for inspiration. Some turn to their computers to take a closer look at the big picture.

The Grand Challenge Cosmology Consortium (GC^3) is a collaboration of cosmologists, astrophysicists, and computer scientists who are modeling the birth and early infancy of the universe. Consortium members use high performance computers at the NSF-supported Supercomputer Centers—the precursor of the current Partnerships for Advanced Computational Infrastructure program—to create a three-dimensional model of the formation of galaxies and large-scale structures in the early universe. The consortium uses some of the most powerful supercomputers available to perform the billions of calculations required to figure out how the universe came to be.

In an effort to understand the role of dark matter in galaxy cluster formation, Michael Norman and Gregory Bryan carried out a simulation at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign in 1994. The simulation produced a model that accurately predicted the number and arrangement of galaxy clusters. The prediction was confirmed by recent observations by an orbiting X-ray satellite. While the simulation did not capture exactly the measurable ratio of luminous gas to dark matter, efforts are underway to improve the model's resolution. "Everyone is motivated to find out what dark matter is," says Norman, "but there is nothing definitive yet."

Perhaps the most intriguing aspect of the GC^3 is its ability to simulate situations never seen by humans. In a public display of computer simulation, members of GC^3 teamed up with IMAX to create the 1996 film *Cosmic Voyage*, a short feature that was nominated for an Academy Award. From the safety of their theater seats, audiences can view the life of the universe, from its explosive, Big Bang birth, to the current hubbub of galaxy life. The film also includes a startling animation of what would happen if two spiral galaxies—like the Milky Way and neighboring Andromeda Galaxy—were to collide.

As Wolszczan, Marcy, Butler, and others continue their search for new planets, other astronomers have found evidence of the most powerful magnetic field ever seen in the universe. They found it by observing the "afterglow" of subatomic particles ejected from a magnetar. This neutron star, illustrated above, has a magnetic field billions of times stronger than any on Earth and one hundred times stronger than any other previously known in the universe.

pulsar. Two of the planets are similar in mass to the Earth, while the mass of the third is about equal to that of our moon. It is unlikely that any of these newly discovered planets support life, because the tiny pulsar around which they orbit constantly bombards them with deadly electromagnetic radiation. Wolszczan's work helps astronomers understand how planets are formed, and his discovery of planets around an object as exotic as a pulsar suggests that planets may be far more common than astronomers had previously thought.

In 1995, four years after Wolszczan's discovery, two Swiss astronomers announced that they had found a fourth new planet, orbiting a star similar to the Sun. Two American astronomers, Geoffrey Marcy and Paul Butler, confirmed the discovery and, the following year, announced that their NSF-supported work culminated in the discovery of another two planets orbiting sun-like stars. Using an array of advanced technologies and sophisticated analytic techniques, Marcy, Butler, and other astronomers have since discovered more extrasolar planets. An especially astonishing discovery was made in 1999 by two independent NSF-supported teams of the first multi-planet system—other than our own—orbiting its own star. At least three planets were found by Marcy, Butler, and others to be circling the star Upsilon Andromedae, making it the first solar system ever seen to mimic our own.

By August 2000, the number of extrasolar planets had topped fifty, and more such sightings were expected. Based on the discovery of these planets, it seems as if the Milky Way is rife with stars supporting planetary systems. But what of the Galaxy itself? Is it a calm stellar metropolis, or are there more mysteries to uncover?

At the Center of the Milky Way

In the mid-eighteenth century, philosopher Immanuel Kant suggested that the Sun and its planets are embedded in a thin disk of stars. Gazing at the diffuse band of light we call the Milky Way on a dark night supports Kant's bold statement. But understanding the nature and appearance of our galaxy is no small feat, for we live within a disk of obscuring gas and dust.

Our Sun is part of a large disk made up of stars and large clouds of molecular and atomic gas in motion around the Galaxy's center. Our solar system orbits this center, located about 30,000 light-years away from Earth, at 500,000 miles per hour. It takes our solar system two hundred million years to make a single orbit of the galaxy.

Astronomers can infer the shape and appearance of our galaxy from elaborate observations, and, as a result, have created maps of our galaxy. Yet parts of the Milky Way remain hidden—blocked by light-years of obscuring material (gas and dust) spread between the stars.

Andrea Ghez is working to penetrate the mysteries of this interstellar material. Ghez is an astronomer at the University of California at Los Angeles and an NSF Young Investigator, a national award given to outstanding faculty at the beginning of their careers. Her observations of the central regions of the Milky Way have permitted her to examine its very heart. Ghez, like many others, theorized that the Galaxy's core is the home of a supermassive black hole. "Although the notion has been around for more than two decades, it has been difficult to prove that [a black hole] exists," says Ghez. Now it appears her observations offer that proof.

Using one of the two W. M. Keck 10-meter telescopes on Mauna Kea in Hawaii, Ghez looked at the innermost regions of the Galaxy's core. For three years, she studied the motions of ninety stars. While scientists already knew that those

Detecting Planets Around Other Stars

In the vastness of the universe, are we humans alone? The answer depends on whether there are other planets that are endowed with the warm climate, diverse chemicals, and stable oceans that provided the conditions for biological evolution to proceed here on Earth.

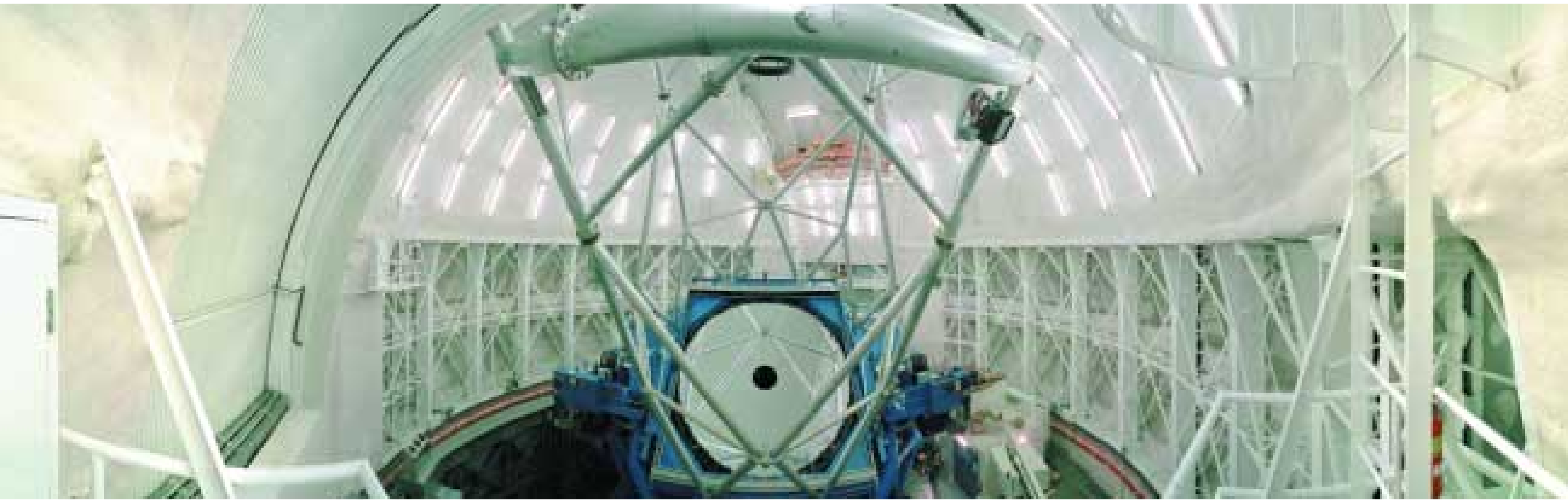
We and other astronomers recently took an important step toward addressing some of these questions when we reported finding that planets do exist outside our own solar system . . . . Already the properties of these extrasolar planets have defied expectations, upsetting existing theories about how planets form.

It took a long time to find extrasolar planets because detecting them from Earth is extraordinarily difficult. Unlike stars, which, like our Sun, glow brightly from the nuclear reactions occurring within, planets shine primarily by light that is reflected off them from their host star.

Astronomers gained the means to find planets around other stars with a clever new technique that involves searching for a telltale wobble in the motion of a star. When planets orbit a star, they exert a gravitational force of attraction on it. The force on the star causes it to be pulled around in a small circle or oval in space. The circle or oval is simply a miniature replica of the planet's orbital path. Two embracing dancers similarly pull each other around in circles due to the attractive forces they exert on each other. This wobble of a star gives away the presence of an orbiting planet, even though the planet cannot be seen directly.

However, this stellar wobble is very difficult to detect from far away. A new technique has proven to be extraordinarily successful. The key is the Doppler effect—the change in the appearance of light waves and other types of waves from an object that is moving away from or toward a viewer. When a star wobbles toward Earth, its light appears from Earth to be shifted more toward the blue, or shorter, wavelength, of the visible light spectrum than it would have if the star had not moved toward Earth. When the star wobbles away from Earth, the opposite effect occurs. The wavelengths are stretched. Light from the star appears to be shifted toward the red, or longer wavelength, end of the spectrum in a phenomenon known as red shift. Astronomers can determine the velocity of a star from the Doppler shift because the Doppler shift is proportional to the speed with which the star approaches or recedes from a viewer on Earth.

—Geoffrey W. Marcy and R. Paul Butler, NSF-funded astronomers at San Francisco State University and the University of California at Berkeley, respectively. Excerpted from "Detecting Planets Around Other Stars," reprinted with permission. Encarta, *May 1997*



The Gemini 8-meter telescope on Mauna Kea, Hawaii, is one of the new tools astronomers are using to search for the barely visible. This telescope, along with other NSF-funded observatories—including Arecibo in Puerto Rico and the Very Large Array in New Mexico—enable astronomers to discover and explain the origins of the universe.

stars nearest the center of the Galaxy move quickly in their orbits, Ghez was astonished to discover that the stars nearest the center of the Milky Way were moving at speeds as high as 3 million miles per hour. Only a very large assembly of superconcentrated mass inside the stars' orbits could whip them around at those speeds. "The high density we observe at the very center of the Milky Way exceeds that inferred for any other galaxy, and leads us to conclude that our galaxy harbors a black hole with a mass 2.6 million times that of the Sun," Ghez notes.

Astronomers do not think that a supermassive black hole at the center of a galaxy is unique to the Milky Way. Rather, it appears to be quite typical of the almost innumerable galaxies in the observable universe. The fact that black holes may be the rule rather than the exception makes it even more important that we continue to study them.

The Origins of the Universe

By observing galaxies formed billions of years ago, astronomers have been able to paint an increasingly detailed picture of how the universe evolved. According to the widely accepted Big Bang theory, our universe was born in an explosive moment approximately fifteen billion years ago. All of the universe's matter and energy—even the fabric of space itself—was compressed into an infinitesimally small volume and then began expanding at an incredible rate. Within minutes, the universe had grown to the size of the solar system and cooled enough so that equal numbers of protons, neutrons, and the simplest atomic nuclei had formed.

After several hundred thousand years of expansion and cooling, neutral atoms—atoms with equal numbers of protons and electrons—were able to form and separate out as distinct entities. Still later, immense gas clouds coalesced to form primitive galaxies and, from them, stars. Our own solar system formed relatively recently—about five billion years ago—when the universe was two-thirds its present size.

In April 2000, an international team of cosmologists supported in part by NSF, released the first detailed images of the universe in its infancy. The images reveal the structure that existed in the universe when it was a tiny fraction of its current age and one thousand times smaller and hotter than today. The project, dubbed BOOMERANG (Balloon

Observations of Millimetric Extragalactic Radiation and Geophysics) captured the images using an extremely sensitive telescope suspended from a balloon that circumnavigated the Antarctic in late 1998. The BOOMERANG images were the first to bring into sharp focus the faint glow of microwave radiation, called the cosmic microwave background, that filled the embryonic universe soon after the Big Bang. Analysis of the images already has shed light on the nature of matter and energy, and indicates that space is "flat."

The roots of the Big Bang theory reach back to 1929, the year Edwin Hubble and his assistant Milton Humason discovered that the universe is expanding. Between 1912 and 1928, astronomer Vesto Slipher used a technique called photographic spectroscopy—the measurement of light spread out into bands by using prisms or diffraction gratings—to examine a number of diffuse, fuzzy patches. Eventually, Hubble used these measurements, referred to as spectra, to show that the patches were actually separate galaxies. Slipher, who did his work at Lowell Observatory in Flagstaff, Arizona, found that in the vast majority of his measurements the spectral lines appeared at longer, or redder, wavelengths. From this he inferred that the galaxies exhibiting such "red shifts" were moving away from Earth, a conclusion he based on the Doppler effect. This effect, discovered by Austrian mathematician and physicist Christian Doppler in 1842, arises from the relative motion between a source and an observer. This relative motion affects wavelengths and frequencies. Shifts in frequency are what make ambulance sirens and train whistles sound higher-pitched as they approach and lower-pitched as they move away.

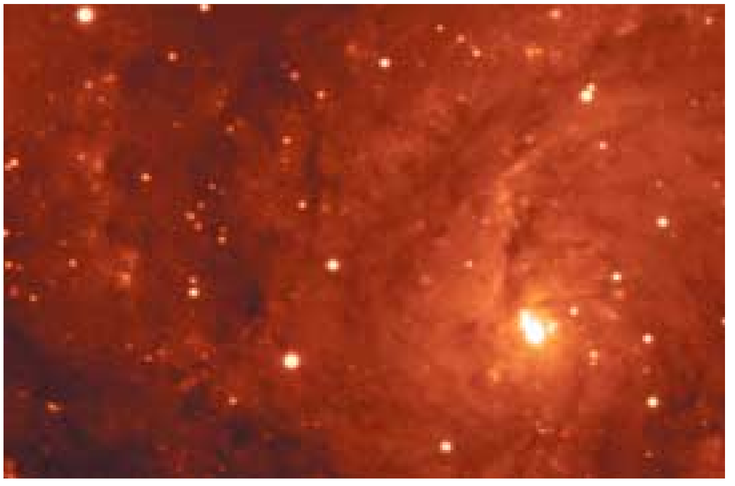
Hubble took these findings and eventually determined the distances to many of Slipher's galaxies. What he found was amazing: The galaxies were definitely moving away from Earth, but, the more distant the galaxy, the faster it retreated. Furthermore, Hubble and Humason discovered that the ratio of a galaxy's speed (as inferred from the amount of red shift) to its distance seemed to be about the same for all of the galaxies they observed. Because velocity appeared proportional to distance, Hubble reasoned, all that remained was to calculate that ratio—the ratio now referred to as the Hubble Constant.

And what is the value of the Hubble Constant? After seventy years of increasingly precise measurements of extragalactic velocities and distances, astronomers are at last closing in on this elusive number.

Wendy Freedman is one of the scientists working to define the Hubble Constant. As head of an international team at the Carnegie Observatories in Pasadena, California, Freedman surveys the heavens using the Hubble Space Telescope to measure distances to other galaxies. With grants from NSF, she is building on the legacy of Henrietta Leavitt, who discovered in the early 1900s that the absolute brightness of Cepheid variable stars is related to the time it takes the stars to pulsate (its period). Scientists can measure the period of a Cepheid in a distant galaxy and measure its apparent brightness. Since they know the period, they know what the absolute brightness should be. The distance from Earth to the Cepheid variable star is inferred from the difference between absolute and apparent brightness. Freedman and her colleagues are using this method to determine distances to other galaxies. With these Cepheid distances, Freedman's group calibrates other distance-determination methods to reach even more far-flung galaxies. This information, in turn, enables them to estimate the Hubble Constant.

Researchers closing in on a definitive value for the Hubble Constant are doing so in the midst of other exciting developments within astronomy. In 1998, two independent teams of astronomers, both with NSF support, concluded that the expansion of the universe is accelerating. Their

Radio telescopes from the NSF-funded Very Large Array in New Mexico are helping astronomers to map our universe.



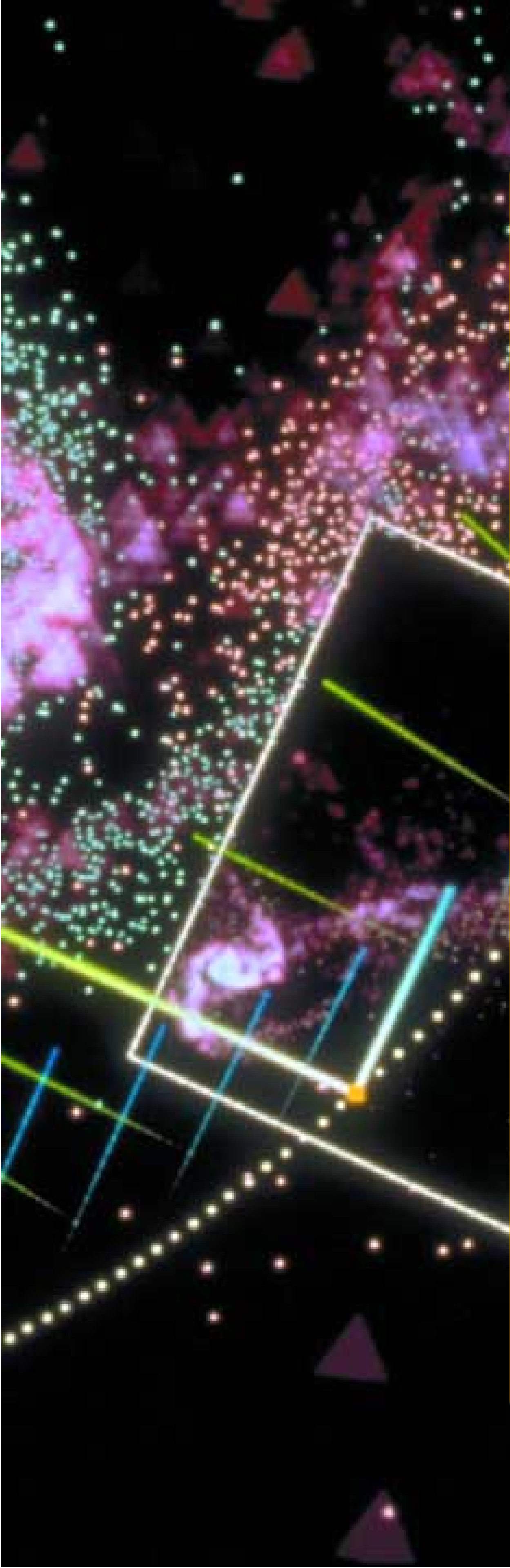
This galaxy in the constellation Cygnus is nearly 20 million light-years from Earth. Galaxies such as this one are helping astronomers understand the expansion of the universe, its density, and organization.

unexpected findings electrified the scientific community with the suggestion that some unknown force was driving the universe to expand at an ever increasing rate. Earlier evidence had supported another possibility, that the gravitational attraction among galaxies would eventually slow the universe's growth. In its annual survey of the news, *Science* magazine named the accelerating universe as the science discovery of the year in 1998.

Jeremy Mould, director of Mount Stromlo and Siding Spring Observatories in Canberra, Australia, has studied another aspect of the expansion of the universe. Scientists generally assume that everything in the universe is moving uniformly away from everything else at a rate given by the Hubble Constant. Mould is interested in departures from this uniform Hubble flow. These motions are known as peculiar velocities of galaxies. Starting in 1992, Mould and his colleague John Huchra of the Harvard Smithsonian Center for Astrophysics used an NSF grant to study peculiar velocities of galaxies by creating a model of the universe and its velocity that had, among other things, galaxy clusters. These galaxies in clusters were accelerated by the gravitational field of all the galaxies in the locality. All other things being equal, a high-density universe produces large changes in velocity. This means that measurements of peculiar velocities of galaxies can be used to map the distribution of matter in the universe. Mould and Huchra's model has seeded major efforts to collect measurements of the actual density of the universe so as to map its mass distribution directly.

In the modular universe—where stars are organized into galaxies, galaxies into clusters, clusters into superclusters—studies of galaxies, such as those conducted by Mould, give us clues to the organization of larger structures. To appreciate Mould's contribution to our understanding of these organizing principles, consider that a rich galaxy cluster can contain thousands of galaxies, and each galaxy can contain tens of billions to hundreds of billions of stars. Astronomers now estimate that there are tens of billions of galaxies in the observable universe. Large, diffuse groupings of galaxies emerging from the empty grandeur of the universe show us how the universe is put together—and perhaps even how it all came to be.

Only one of those extragalactic islands of stars—the Andromeda Galaxy—is faintly visible to the naked eye from the Northern Hemisphere, while two small satellite galaxies of the Milky Way—the Large and Small Magellanic Clouds—can be seen from Earth's Southern Hemisphere. Telescopes augmented with various technologies have enabled astronomers—notably NSF grantee Gregory Bothun of the University of Oregon—to discover galaxies that, because of their extreme diffuseness, went undetected until the 1980s. These "low-surface-brightness" galaxies effectively are masked by the noise of the night sky, making their detection a painstaking process. More than one thousand of these very diffuse galaxies have been discovered in the past decade, but this is only the beginning. "Remarkably, these galaxies may be as numerous as all other galaxies combined," says Bothun. "In other words, up to 50 percent of the general galaxy population of the universe has been missed, and this has important implications with respect to where matter is located in the universe."



Why Cosmology?

Cosmologists work to understand how the universe came into being, why it looks as it does now, and what the future holds. They make astronomical observations that probe billions of years into the past, to the edge of the knowable universe. They seek the bases of scientific understanding, using the tools of modern physics, and fashion theories that provide unified and testable models of the evolution of the universe from its creation to the present, and into the future . . . .

Do physics and cosmology offer a plausible description of creation? As cosmologists and physicists push the boundary of our understanding of the universe ever closer to its beginning, one has to wonder whether the creation event itself is explainable by physics as we know it, or can ever know it . . . .

Clearly, these questions are at the heart of humankind's quest to understand our place in the cosmos. They involve some of the most fundamental unanswered questions of physical science. But why, in a time of great national needs and budget deficits, should the U.S. taxpayer support such seemingly impractical research . . . ?

In fact, far from being impractical, cosmological research produces important benefits for the nation and the world. . . . [I]t has unique technical spinoffs. Forefront research in cosmology drives developments in instrumentation for the collection, manipulation, and detection of radiation at radio, infrared, visible, ultraviolet, X-ray, and gamma-ray wavelengths. The understanding and application of such types of radiation are the foundation for many important technologies, such as radar, communications, remote sensing, radiology, and many more . . . .

Our cosmology—every culture's cosmology—serves as an ethical foundation stone, rarely acknowledged but vital to the long-term survival of our culture . . . . For example, the notion of Earth as a limitless, indestructible home for humanity is vanishing as we realize that we live on a tiny spaceship of limited resources in a hostile environment. How can our species make the best of that? Cosmological time scales also offer a sobering perspective for viewing human behavior. Nature seems to be offering us millions, perhaps billions, of years of habitation on Earth. How can we increase the chances that humans can survive for a significant fraction of that time? Cosmology can turn humanity's thoughts outward and forward, to chart the backdrop against which the possible futures of our species can be measured. This is not irrelevant knowledge; it is vital.

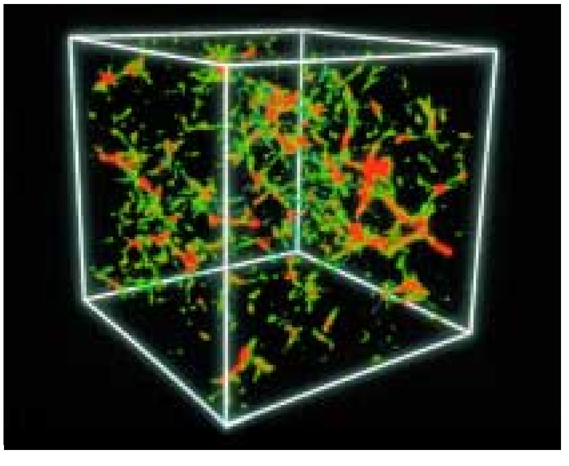
—*Excerpted from* Cosmology: A Research Briefing. *Reprinted with permission of the National Research Council, National Academy of Sciences.*

The Hunt for Dark Matter

Even with all of the galaxies that Bothun and others expect to find, researchers still say much of the matter in the universe is unaccounted for.

According to the Big Bang theory, the nuclei of simple atoms such as hydrogen and helium would have started forming when the universe was about one second old. These processes yielded certain well-specified abundances of the elements deuterium (hydrogen with an extra neutron), helium, and lithium. Extensive observations and experiments appear to confirm the theory's predictions within specified uncertainties, provided one of two assumptions is made: (1) the total density of the universe is insufficient to keep it from expanding forever, or (2) the dominant mass component of the universe is not ordinary matter. Theorists who favor the second assumption need to find more mass in the universe, so they must infer a mass component that is not ordinary matter.

Part of the evidence for the second theory was compiled by Vera Rubin, an astronomer at the Carnegie Institution of Washington who received NSF funding to study orbital speeds of gas around the centers of galaxies. After clocking orbital speeds, Rubin used these measurements to examine the galaxies' rotational or orbital speeds and found that the speeds do not diminish near the edges. This was a profound discovery, because scientists previously imagined that objects in a galaxy would orbit the center in the same way the planets in our galaxy orbit the Sun. In our galaxy, planets nearer the Sun orbit much faster than do those further away (Pluto's orbital speed is about one-tenth that of Mercury). But stars in the outer arms of the Milky Way spiral do not orbit slowly, as expected; they move as fast as the ones near the center.



Dark matter makes up most of the universe, but no one knows how much of it there is. Researchers use computer simulations such as this one to test different ratios of cold and hot (dark) matter in an attempt to learn more about the components of our universe

What compels the material in the Milky Way's outer reaches to move so fast? It is the gravitational attraction of matter that we cannot see, at any wavelength. Whatever this matter is, there is much of it. In order to have such a strong gravitational pull, the invisible substance must be five to ten times more massive than the matter we can see. Astronomers now estimate that 90 to 99 percent of the total mass of the universe is this dark matter—it's out there, and we can see its gravitational effects, but no one knows what it is.

At one of NSF's Science and Technology Centers, the Center for Particle Astrophysics at the University of California at Berkeley, investigators are exploring a theory that dark matter consists of subatomic particles dubbed WIMPs, or "weakly interacting massive particles." These heavy particles generally pass undetected through ordinary matter. Center researchers Bernard Sadoulet and Walter Stockwell have devised an experiment in which a large crystal is cooled to almost absolute zero. This cooling restricts the movements of crystal atoms, permitting any heat generated by an interaction between a WIMP and the atoms to be recorded by monitoring instruments. A similar WIMP-detection project is under way in Antarctica, where the NSF-supported Antarctic Muon and Neutrino Detector Array (AMANDA) project uses the Antarctic ice sheet as the detector.

In the spring of 2000, NSF-supported astrophysicists made the first observations of an effect predicted by Einstein that may prove crucial in the measurement of dark matter. Einstein argued that gravity bends light. The researchers studied light from 145,000 very distant galaxies for evidence of distortion produced by the gravitational pull of dark matter, an effect called cosmic shear. By analyzing the cosmic shear in thousands of galaxies, the researchers were able to determine the distribution of dark matter over large regions of the sky.

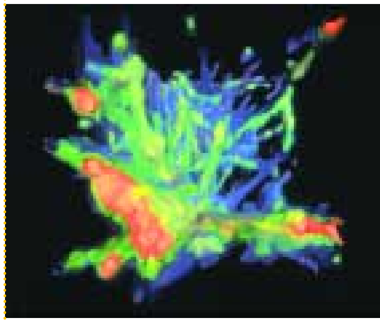
Cosmic shear "measures the structure of dark matter in the universe in a way that no other observational measurement can," says Anthony Tyson of Bell Labs, one of the report's authors. "We now have a powerful tool to test the foundations of cosmology."

Shedding Light on Cosmic Voids

Even with more than 90 percent of its mass dark, the universe has revealed enough secrets to permit initial efforts at mapping its large-scale structure. Improved technologies have enabled astronomers to detect red shifts and infer velocities and distances for many thousands of galaxies. New research projects will plumb the secrets of nearly one million more. And yet, we have much more to learn from the hundreds of billions of galaxies still unexplored.

Helping in the exploration is an ingenious method, developed with help from NSF, that is commonly used to estimate distances to and map the locations of remote galaxies. R. Brent Tully of the University of Hawaii and his colleague at the NSF-funded National Radio Astronomy Observatory, J. Richard Fisher, discovered that the brighter a galaxy—that is, the larger or more massive it is, after correcting for distance—the faster it rotates. Using this relationship, scientists can measure the rotation speed of a galaxy. Once that is known, they know how bright the galaxy should be. Comparing this with its apparent brightness allows scientists to estimate the galaxy's distance. The Tully-Fisher method, when properly calibrated using Cepheid variable stars, is proving to be an essential tool for mapping the universe.

In early 2000, researchers announced the discovery of a previously unknown quasar that qualified as the oldest ever found—indeed, as among the earliest structures to form in the universe. Quasars are extremely luminous bodies that emit up to ten thousand times the energy of the Milky Way. Eventually our maps will include everything we know about the universe—its newly revealed planets, the inner workings of the stars, distant nebula, and mysterious black holes. With our map in hand and our new understanding of how the universe began and continues to grow, we humans will have a better chance to understand our place in the vast cosmos.



Researchers at the Electronic Visualization Laboratory at the University of Illinois at Chicago used data provided by astronomers to create this image of our universe.

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www.naic.edu/aboutao.htm

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www.noao.edu

National Center for Supercomputing Applications
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Whispers from the Cosmos
www.ncsa.uiuc.edu/Cyberia/Bima/BimaHome.html

Cosmos in a Computer
www.ncsa.uiuc.edu/Cyberia/Cosmos/CosmosCompHome.html

Center for Particle Astrophysics
http://cfpa.berkeley.edu/home.html

NSF Division of Astronomical Sciences
www.nsf.gov/mps/ast

Global Oscillation Network Group (GONG)
www.gong.noao.edu/index.html

Grand Challenge Cosmology Consortium (GC^3)
http://zeus.ncsa.uiuc.edu:8080/GC3_Home_Page.html

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www.nrao.edu

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