NEWS

The Warped Side of Dark Matter

Weak gravitational lensing, a subtle distortion of all distant galaxies, promises the most direct way of mapping the universe we can't see

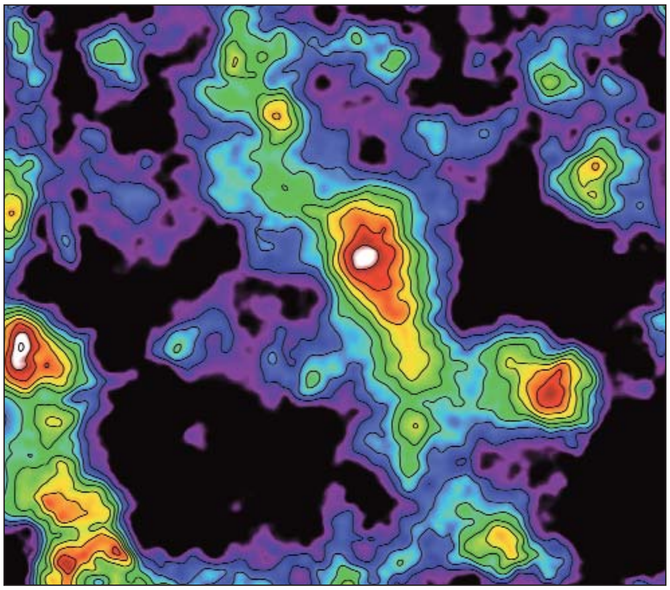
Imagine flying over a mountain range on a moonless night. You know that peaks loom below, but you can't see them. Suddenly, specks of light pop into view: isolated country homes, dotting the hilly slopes. The lights outline part of the massive edifice, but your mind grasps that the darkness hides something far larger.

Astronomers face a similar situation. In recent years, their research has confirmed that the luminous universe—our sun, our galaxy, and everything that shines—makes up but a wee bit of all there is. Instead, the strange new recipe calls for more than one-quarter "dark matter" and two-thirds "dark energy." This is the universe your teacher never told you about: matter of a completely unknown nature and energy that hastens the expansion of the cosmos toward future oblivion.

To divine the properties of dark matter, astronomers first must find out where it is. And to learn how dark energy controls the fate and shape of the universe—including how matter is distributed—they must trace how the dark matter clumped together over time. But they can't see it; all they have are some bright dots in a vast, mountainous wilderness.

That's about to change. Researchers are refining an exciting new technique that relies on the warping of space itself to reveal dark matter. Called weak gravitational lensing, the method exposes dark matter by tracing the subtle distortions it imparts to the shapes and alignments of millions of distant galaxies. The effect isn't obvious to the eye, yet it alters the appearance of every remote galaxy. Although widespread detection of this "cosmic shear" first hit journals just 3 years ago, several teams worldwide have embarked on major new surveys in a race to exploit its potential. Indeed, astronomers now feel that weak lensing will become a cornerstone of modern cosmology, along with studies of the cosmic microwave background radiation and distant explosions of supernovas.

"I no longer regard galaxies as tracers of the cosmos," says astronomer Richard Ellis of the California Institute of Technology (Caltech) in Pasadena. "We now have the confidence to go after the real physics. Let's image the dark matter directly; we have the tools to do it. Weak lensing is one of the cleanest cosmic probes of all."



Brought to light. Weak gravitational lensing exposed these patches of dark matter, otherwise hidden from telescopes.

CREDIT: J. A. TYSON AND D. M. WITTMAN/DEEP LENS SURVEY

Line up and stretch

Weak lensing is akin to the far more spectacular process called strong gravitational lensing. In the latter, the intense gravity of galaxies or clusters of galaxies bends and magnifies light from more distant objects as the light travels toward Earth. Strong lensing can split a single quasar into four images or distort remote clusters into dizzying swirls of eerie arcs. These funhouse mirrors in space, captured exquisitely by the Hubble Space Telescope, are vivid displays of the pervasive light-bending effects in Albert Einstein's general theory of relativity.

Relativity also causes weak lensing, but without such drama. "Strong lensing is like pornography: You know it when you see it," says astronomer R. Michael Jarvis of the University of Pennsylvania in Philadelphia. "Weak lensing is like art." And like art critics, astronomers have honed their perception to see weak lensing where others see a featureless array of galaxies.

The array is a background of millions of faint blue galaxies, first recognized in the late 1980s. This "giant tapestry," in the words of astronomer Ludovic Van Waerbeke of the Institute of Astrophysics in Paris (IAP), freckles any exposure of the heavens by research telescopes with mirrors larger than 2 meters across. The galaxies date to a time when the universe was less than half its current age, and they are everywhere astronomers look.

Although each galaxy looks like a disk or an elongated blob, the mathematical average of a large number of them is a round shape. In a similar way, the galaxies should not line up in a special direction; on average, their orientations should be random. Weak lensing, induced by the tugging of dark matter between us and the faint galaxies, leaves patterns in those shapes and alignments at a tiny level of distortion: about 1%. Finding the patterns thus becomes a statistical game. "Each galaxy is like a little stick on the sky, and we want to measure its elongation and orientation," Van Waerbeke says. To see that signal reliably, astronomers must take steady photos of the galactic tapestry. Useful images typically capture at least 20,000 galaxies in a patch of sky the size of the full moon—one-fifth of a square degree.

Then, using the physics of relativity, the researchers convert the slight distortions into a plot of all of the mass—both luminous and dark—along the path between Earth and the distant galaxies. This plot (see figure at left) is a two-dimensional projection; it doesn't reveal the distance to each blob. Even so, it exposes unseen mountains of mass whose gravity changes the appearance of everything on their far sides. "To see this, we don't have to make assumptions about what the dark matter is," says astronomer Jason Rhodes of Caltech. "It's the most direct way to simply measure everything that's there."

Of course, there are complications. The atmosphere blurs galaxies, telescopes jitter, and electronic detectors have flaws. Statistics quickly degrade unless images are rock solid over a wide patch of sky. But the promise of weak lensing was so potent in the late 1990s that a spirited race pushed astronomers to tackle these technology issues.

When success came, it came with a flash: four nearly simultaneous papers in March 2000 from groups in Canada, Europe, and the United States on the first detections of cosmic shear over large areas.

Since then, teams have extended their efforts in two ways. Some look at broader sweeps of the sky with modest telescopes, such as the 3.6-meter Canada-France-Hawaii Telescope (CFHT) on Mauna Kea, Hawaii, and the 4.2-meter William Herschel Telescope on La Palma, Canary Islands. Those projects aim to examine as many dark-matter patches as possible in a sort of population survey, improving the overall statistics of their distribution through the universe. Others use big telescopes, including one of the European Southern Observatory's four 8.2-meter Very Large Telescopes on Cerro Paranal, Chile, and one of the twin 10-meter Keck Telescopes on Mauna Kea, to zero in on a few distant regions with greater depth.

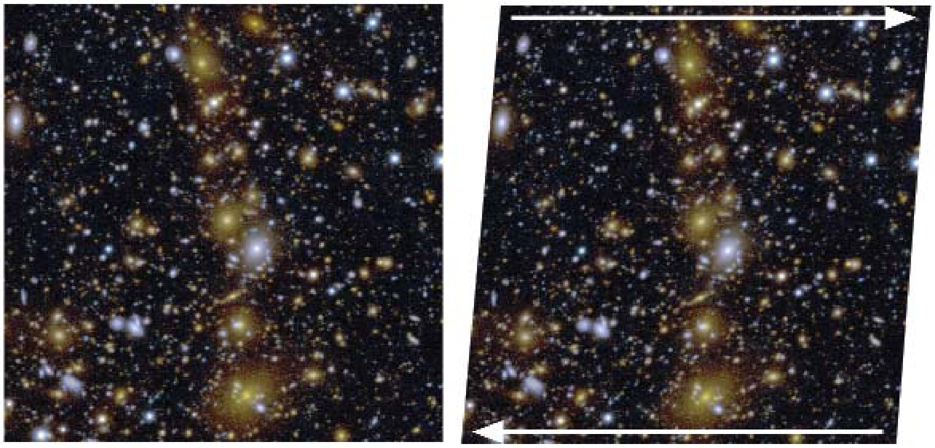
Most of the invisible mass found by weak lensing is mingled with ordinary galaxies visible in either optical light or x-rays. However, some teams claim to have spotted concentrations of matter with no associated galaxies at all. These truly dark clusters, if they are real, would betray the universe's dirty secret: Big piles of mass don't necessarily come with lights attached.

Most agree that shaky statistics make those claims vague for now, but the fundamental lesson is valid. "The ratio between emitted light and underlying mass changes quite considerably" from cluster to cluster, says theorist Matthias Bartelmann of the Max Planck Institute for Astrophysics in Garching, Germany. "This is something unexpected."

The implication is profound. Astronomers cannot rely on large-scale surveys of galaxies alone to trace the history of how matter has assembled in the universe. But that history is critical to unraveling the riddle of dark energy. As Bartelmann notes, dark energy apparently has exerted its greatest influence during the past several billion years. As the expansion of space carried matter farther apart, gravity became less effective at slowing the expansion. Meanwhile, dark energy—manifested as a self-repulsion within the fabric of space itself—grew dominant (see p. 1896).

Theorists are eager for an atlas of how dark matter clumped together to help them see what makes dark energy tick. "We have no other way to calibrate how structures formed in an unbiased way in the last one-third of cosmic evolution," when dark energy's sway took hold, Bartelmann says. "Weak lensing is without competition in that field."

Teams already are taking a first crack at measuring the clumpiness of dark matter. In essence, a smooth spread of dark matter between us and a distant galaxy has a minor lensing effect, whereas blobs of the stuff enhance the weak-lensing signal—just as marbled glass on a thick shower door distorts light more than plate glass does. Even with current statistics, results from weak-lensing surveys help pin down numbers for the mass content and expansion rate of the universe, according to a paper in press at *Physical Review Letters* by astrophysicist Carlo Contaldi of the Canadian Institute for Theoretical Astrophysics in Toronto and colleagues. "The combination of [cosmic microwave background radiation] and weak-lensing data provides some of the most powerful constraints available in cosmology today," the team writes.



Shear science. Distant galaxies show random shapes and orientations (*left*) unless intervening dark matter shears those patterns in a subtle but detectable way (*right*).

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Another promising way to chart dark matter's behavior is "3D mass tomography," named by a pioneer of weak lensing, astrophysicist J. Anthony Tyson of Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, and his colleague David Wittman. Researchers can gauge the distances to blobs of dark matter by crudely estimating the distance to each distorted galaxy in the background tapestry. Light from the most distant galaxies crosses the greatest chasm of space and gets lensed most severely, whereas relatively nearby galaxies aren't affected as much.

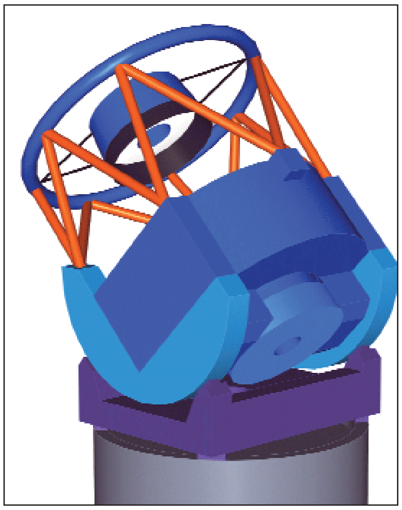
By correlating the distortions of galaxies with their rough distances, Tyson's team can convert the 2D projections of total mass into 3D volumes. That reveals where the dark-matter mountains are in space with 10% to 20% accuracy. Using data from the 4-meter National Optical Astronomy Observatory telescopes at Kitt Peak, Arizona, and Cerro Tololo, Chile, the group has derived locations for about two dozen dark clusters. When the astronomers complete their survey of 28 square degrees of the sky in 2004, they expect to identify 200 clusters out to a distance of about 7 billion light-years, says Wittman.

Take a wider view

Still, Tyson's program and all other efforts face similar problems: Images aren't sharp enough, deep enough, or wide enough. "The facilities we have worldwide don't yet have the light grasp and field of view required to get the scientific promise out of weak lensing," Tyson says.

Astronomers are launching a second generation of cosmic-shear surveys that should achieve some of that promise. Foremost is the CFHT Legacy Survey, powered by the biggest astronomical camera ever built: MegaPrime, which can take sharp images of a full square degree of sky (five full moons). The 170-square-degree survey, set to begin within weeks, will consume 100 nights per year for 5 years on the CFHT. Goals include searching for supernovas and nearby transient objects, such as hazardous asteroids. However, the weak-lensing part of the survey—led by IAP astronomer Yannick Mellier—has the community abuzz. "MegaPrime is a magnificent instrument, and this survey will be a landmark in the field," says Caltech's Ellis.

A hot competitor is one of CFHT's neighbors under the crisp Mauna Kea skies: Japan's 8.2-meter Subaru Telescope and its new Suprime-Cam. Although its field of view is just one-fourth that of MegaPrime, Suprime-Cam has won equal raves for its image quality. Moreover, Subaru's mirror has more than four times as much light-collecting power as does CFHT. That will let the Japanese team examine lenses in far greater detail. The astronomers plan to use 3D tomography to pinpoint the masses, distances, and rough shapes of hundreds of dark entities. "We would like to publish the first mass-selected object catalog [of dark-matter lenses] in a timely manner," says team leader Satoshi Miyazaki of the National Astronomical Observatory of Japan in Hilo, Hawaii.



Wide eye. The Large Synoptic Survey Telescope will look for dark-matter warping.

These and other planned surveys will set the stage for weak lensing's coup de grâce next decade. Tyson leads a large U.S. team that is working on the Large Synoptic Survey Telescope (LSST), a project that has won top billing for ground-based astronomy from national review panels. A radical optical design of one 8.4-meter mirror and two other mirrors larger than 4 meters will open up a giant swath of sky—at least 7 square degrees—for LSST to see at once. Among many projects, LSST will discover 300,000 mass clusters and tighten the errors on cosmic parameters—such as the dark energy "equation of state," a measure of its physical cause—to about 2%, Tyson predicts. He hopes observations will begin by 2011.

At about the same time, supernova researchers led by astrophysicist Saul Perlmutter of Lawrence Berkeley National Laboratory in California hope to launch the SuperNova Acceleration Probe (SNAP). The satellite, an ambitious proposal to study dark energy by tracing the expansion history of the universe more than 10 billion years into the past, will carry a wide-field 2-meter telescope ideal for measuring weak lensing as well. Current plans call for SNAP to devote 32 months to supernova searches and 5 months to a weak-lensing survey spanning at least 300 square degrees, Perlmutter says.

Lensing aficionados hope to avoid a battle for funding between the two expensive approaches. Research on the cosmic microwave background radiation showed that cleverly designed telescopes on the ground and on balloons could answer key questions. Then, the Wilkinson Microwave Anisotropy Probe satellite nailed the answers beyond doubt from the quiet of space. In a similar vein, outside observers think that both future lensing projects should proceed. Still, some believe that SNAP may yield the most stunning results. "We need to measure the shapes of galaxies as accurately as possible, and we have problems [doing that] from the ground," says Van Waerbeke of IAP. "But from space, it's just perfect."

That debate may sharpen as weak lensing becomes more widely known, but so will the basic shift in how we study the cosmos. "The universe is not those pinpoints of light we can see in the night," Tyson says. "It is in fact this dark side. In some sense, we are using what most people *thought* was the universe, namely radiation and light, as a tool to measure the real universe for the first time." As that door opens, we will grow accustomed to a warped universe where no shining object is quite as it appears.

–ROBERT IRION

NEWS

Dark Energy Tiptoes Toward the Spotlight

Discovered less than a decade ago, a mysterious antigravity force suffuses the universe. Physicists are now trying to figure out the properties of this "dark energy"—the blackest mystery in the shadiest realms of cosmology

It's the biggest question in physics: What is the invisible stuff blowing the universe apart? A decade ago, the idea of "dark energy" was a historical footnote, something Einstein concocted to balance his equations and later regretted. Now, thanks to observations of distant supernovae and the faint afterglow of the big bang, dark energy is weighing ever more heavily upon the minds of cosmologists. They now know that this mysterious "antigravity" force exists, yet nobody has a good explanation for what it might be or how it works.

That vexing state of affairs may be starting to change. Scientists are finally beginning to get the first tentative measurements of the properties of this ineffable force. It's a crucial endeavor, because the nature of dark energy holds the secret to the fate of the universe and might even cause its violent and sudden demise.

"We're off to a very good start," says Adam Riess, an astronomer at the University of California (UC), Berkeley, who hints that within the next few months, supernova observations will finally help scientists begin to shine light on dark energy.

The modern story of dark energy began in 1997 when supernova hunters such as Riess and Saul Perlmutter of Lawrence Berkeley National Laboratory in California shocked the scientific community by showing that the universe is expanding ever faster rather than slowing down as physicists expected. They based that conclusion on observations of large numbers of supernovae known as type Ia. Because every type Ia explodes in roughly the same way with roughly the same brightness, the astronomers could use characteristics of their light to determine how far away the supernovae are (which is equivalent to determining how old they are) and how fast they're moving. When they calculated how fast the universe had been expanding at various times in the past, the results were "a big surprise," says Perlmutter: The universe has been expanding faster and faster rather than slowing down.

On the face of it, this was an absurd conclusion. As far as most physicists were concerned, only two big forces had shaped the universe. First, the energy of the big bang caused the early universe to expand very rapidly; then as the energy and matter in the universe condensed into particles, stars, and galaxies, the mutual gravitation of the mass started putting on the brakes.

The supernova data showed that something else has been going on. It is as if some mysterious antigravity force is making the fabric of the universe inflate faster than gravity can make it collapse (*Science*, 30 January 1998, p. 651). Observations of the cosmic microwave background radiation bolstered the case. By looking at the patchiness in the microwave radiation from the early universe, cosmologists could see that the universe as a whole is "flat": The fabric of spacetime has no curvature (*Science*, 28 April 2000, p. 595). Yet there is far too little matter in the universe to pull it into such a shape. There has to be an unknown energy—dark energy—suffusing the uni-

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