

EXPLORING THE UNIVERSE THROUGH **GRAVITY**



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Tales from the dark side

What do we really know

Some type of mysterious, invisible mass holds the universe together. Here's how scientists are searching for it. **by Liz Kruesi**

he universe doesn't abide by "what you see is what you get." In fact, the stuff we see in space — stars, gas, and dust — accounts for only 10 percent of the universe's mass. This visible stuff is ordinary matter, and it's made up of protons, neutrons, and electrons. Scientists call ordinary matter "baryonic matter" because protons and neutrons are subatomic particles called baryons. The other 90 percent of the mass is "dark matter," and it likely surrounds almost every galaxy in the universe.

Dark matter doesn't emit, absorb, or reflect any type of light (so, for example,

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it doesn't emit X-rays or absorb infrared radiation). This mysterious stuff is therefore invisible, yet astronomers learned it exists because dark matter interacts with ordinary matter through gravity.

Searching in the dark

Swiss astrophysicist Fritz Zwicky first proposed dark matter's existence in 1933. While studying the Coma cluster of galaxies, he found that the galaxies' collective gravity alone was much too small to hold the cluster together.

The next round of evidence came in the 1970s. Astronomers charted the velocities of stars at various distances from the center of a spiral galaxy and plotted the velocity versus the distance to create a "rotation curve." They expected the velocities to reach a maximum and then decrease farther from the center but the data showed otherwise. The velocities reach a maximum and then plateau. With velocities so high at the outer edge of galaxies, the stars should fling out of their orbits. But they don't. Some sort of mass scientists can't detect must be holding these outer stars in orbit.

A very massive object — such as a galaxy cluster — can act as a gravitational lens. Some images of regions around galaxy clusters show numerous arcs. Those are background galaxies distorted and magnified by the cluster's gravity.

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about dark matter?

Massive galaxy clusters like Abell 2218 have provided scientists with evidence for the existence of dark matter. By analyzing the arcs — warped images of a background galaxy — surrounding the cluster center, astronomers determined the cluster must have a lot more mass than meets the eye. NASA/Andrew Fruchter/ERO Team (Sylvia Baggett (STSci), Richard Hook (ST-ECF), Zoltan Levay (STSci)) (STSci)

Astronomers study the sizes and shapes of those arcs to determine a cluster's mass. By comparing that calculated mass to the mass that comes from only luminous objects (the galaxies), astronomers can determine how much dark matter is in a cluster.

Other evidence has turned up in collisions of galaxy clusters, namely the Bullet cluster. This object is actually the aftermath of two galaxy clusters that collided. Astronomers used a multidetection approach to look at the galaxies, gas, and dark matter. When the clusters collided, the galaxies' stars passed through mostly unaffected because a lot of space exists between the stars. The clusters' hot gas makes up most of their baryonic mass. Ordinary matter interacts through electromagnetic forces. Thus, as matter collides it loses energy as radiation (in the form of X-rays, in this case). The hot gas slows during the collision.

Astronomers use gravitational lensing to indirectly map the dark matter distribution. It turns out that dark matter also passed through the collision unaffected. So images of the Bullet cluster show direct evidence of dark matter.

The evidence is piling up — with 3-D dark matter maps and other detections. Yet mapping the distribution is one thing; knowing the characteristics of this mysterious stuff is another story.

Unlike anything we've seen

For many years astronomers thought dark matter could consist of dead stars, black holes, and other known objects that emit little or no light. They used gravitational microlensing to look for these objects. This technique is similar to gravitational lensing except the foreground object is much less massive. Instead of light bending around the object, the body's gravity magnifies the light from behind it. While astronomers found some of these MAssive Compact Halo Objects (MACHOs), there weren't enough to account for all of the universe's missing mass.

So if dark matter isn't composed of normal objects, then it likely consists of



Two massive galaxy clusters collided to form what's known as the Bullet cluster of galaxies. Ordinary matter — the hot gas, shown in pink — collided, lost energy, and slowed. The clusters' dark matter (shown in blue) interacted little and passed through the ordinary matter.

non-baryonic particles — meaning it's not made up of the same stuff as ordinary matter (protons and neutrons). Astronomers split non-baryonic dark matter into two categories: hot and cold. These titles have nothing to do with temperature. Hot means that early in the universe these particles traveled extremely fast almost at the speed of light. Cold means that early in the universe the particles traveled more slowly.

How does particle speed relate to dark matter's composition? Slower particles will bunch up into small structures earlier in the universe. Those small structures will eventually collide and merge to form larger ones. Astronomers believe this is how structure develops and evolves in our universe: Smaller structures eventually merge into the massive superclusters we observe today. Astronomers simulate structure evolution with cold dark matter (CDM) and can create models that resemble today's universe.

What is CDM? Scientists aren't sure yet. They have a couple of options that branch from particle physics — but none contrived just to fit into dark matter theories. "Both [options] are generated by particle theories having nothing to do with dark matter," says Juan Collar of the University of Chicago. "However, these hypothetical particles turn out to have all of the properties (mass, abundance, lifetime, probability, and mode of interaction) required to be the dark matter, or at least a fraction of it."

For decades, physicists have worked to explain how the four fundamental physical forces fit together. (These forces are gravitation, electromagnetism, weak nuclear, and strong nuclear.) In the past 30 or so years, they've arrived at supersymmetry theory. This model predicts



Astronomers were surprised to find that stars far from a galaxy's core travel at speeds similar to those close in. John Smith

that each ordinary particle (such as an electron or quark) has a massive "superpartner" (a selectron or squark) that remains undetected.

The leading dark matter candidate is a class of particles that supersymmetry predicts. These particles have mass and interact through the weak nuclear force, but they don't interact through the electromagnetic force. Because these weakly interacting massive particles (WIMPs) interact via the weak force, they can collide with normal atomic nuclei and bounce off them without emitting light or absorbing radiation. The lightest WIMP — called the neutralino — is also the most popular dark matter possibility.

Another common CDM candidate is the axion. The axion is also a hypothetical particle, but it arises from a theory different from supersymmetry. This particle is not a "matter particle" but instead a force carrier, similar to the photon (which "carries" the electromagnetic force). It's much lighter than a WIMP at least 1 billion times less massive — so the universe would need a whole lot more axions than WIMPs to make up all the invisible matter.

One would expect that with so many CDM particles, WIMPs or axions would be easy to find. But because they don't interact through the electromagnetic force, detecting them pushes scientists' experimental limits.

How to hunt CDM

The method used to detect dark matter depends on what type of dark matter (WIMP or axion) scientists pursue. Scientists looking for WIMPs try to directly observe the interaction with ordinary



A galaxy's rotation curve compares the disk stars' velocities with their distances from the galaxy's center. *Astronomy:* Roen Kelly



The universe's structure seems to evolve as smaller clumps bunch to form larger structures. Astronomers simulate structure evolution with cold dark matter and create models that resemble today's universe. This simulation shows dark matter distribution, where brighter areas represent more dense regions.

matter in a detector. A WIMP can collide with an atomic nucleus and move, or "scatter," the nucleus.

Another method is to indirectly detect dark matter. A WIMP's antiparticle is itself, so if two WIMPs interact, they annihilate each other and produce a shower of secondary particles. Astrophysicists can observe many of these secondary particles — such as electrons, positrons (the electron's antiparticle), gamma rays, and neutrinos.

Scientists' methods to locate axions are "totally different than the direct and indirect detection methods used to look for WIMPs," says Dan Hooper of Fermi National Accelerator Laboratory in Batavia, Illinois. When an axion traverses a detector that has a magnetic field, it will convert into a photon.

Instead of trying to detect CDM particles, some scientists aim to create the particles — WIMPs and axions — in the laboratory. To do this, they have to generate extremely high energies, similar to those shortly after the Big Bang. Only particle accelerators have this ability. After the Large Hadron Collider (the world's largest particle accelerator, located in Switzerland) comes back online late this year, scientists should be able to look for hypothetical particles that may make up dark matter.

Bullying the WIMPs

Astronomers believe a spherical halo of CDM surrounds the luminous galactic disk of the Milky Way (and similar halos encase most other galaxies). As our solar system travels around the galaxy's center,
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Supercluster Abell 901/902 contains hundreds of galaxies. Astronomers analyzed the distortion of some 60,000 background galaxies' shapes to determine the supercluster's distribution of dark matter. They then combined a visible-light image of the supercluster with the dark matter distribution map (shown as a magenta haze).

it moves through this dark matter haze. These particles aren't the only things Earth collides with as it moves through the haze. Incoming high-energy ordinary particles called cosmic rays bombard Earth constantly. Radiation from the Sun and more distant sources do, too.

Scientists seek the WIMPs that may compose the CDM haze by placing most dark matter detectors underground and shielding them to block the detector material from cosmic rays. The key is to be able to block signals from "background noise" and detect when a dark matter particle interacts with the material. And if they can't block all of the noise, they must be able to tell the difference between noise and a WIMP.

Some scientists think about 600 million WIMPs pass through a square meter of Earth's surface every second. But remember that they interact weakly. So how do detectors "see" a WIMP? During a rare collision, the WIMP will transfer some of its energy to an atom's nucleus of the detector material, and, as a result, the nucleus scatters (think of pool balls). The amount the nucleus moves (or "recoils") is related to the WIMP's energy. Scientists detect this recoil a few different ways.



The balloon-borne detector Advanced Thin Ionization Calorimeter (ATIC) found a nearby source of mysterious cosmic rays. The source could be a dark matter cloud.

Crumbs along the trail

A group using a balloon-borne detector last November disclosed a previously unknown source of high-energy electrons (cosmic rays). Cosmic-ray particles tend to lose much of their energy by the time they traverse the galaxy and Earth's atmosphere. So scientists typically detect low-energy cosmic rays near Earth's surface. The high-energy electrons that the Advanced Thin Ionization Calorimeter (ATIC) group found indicate the electrons are coming from a nearby source — within about 3,000 light-years.

By analyzing the electrons' detected energies, scientists can determine the energy the particles had before traversing the atmosphere. That energy matches what scientists expect from the products of a possible cold dark matter particle's annihilation. When two Kaluza-Klein (KK) particles meet, they annihilate each other and produce an electron and its antiparticle, the positron. (ATIC can't tell the difference between electrons and positrons, so its electron detection is a total number of electrons and positrons.) If the detected particles truly are products from KK annihilation, then our solar system may be passing through or near a large clump of KK dark matter.

However, these high-energy electrons could also arise from an undiscovered pulsar or other object. And more recent observations by the Fermi Gamma-ray Space Telescope cast doubt on the ATIC observations.

A group using a different detector — the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite — reported in 2008 that it saw a higher-than-expected number of positrons. PAMELA looks at energies lower than ATIC. Some scientists think that PAMELA may have observed positrons from another dark matter particle's annihilation. — L. K.

One type of detector uses crystals kept at frigid temperatures (only 0.01 degree above absolute zero). Crystals have a set structure, so when a WIMP collides with an atomic nucleus, the nucleus recoils and rams into surrounding structure. In these collisions, the scattered nucleus transfers some of its kinetic energy and slightly heats the material. The frigidity ensures that the detected vibrations have resulted from only incoming particle interactions. Of course, the scientists will likely detect particles other than just WIMPs. So most WIMP detectors use multiple methods to determine "on an event-by-event basis if what took place looked like a dark matter particle interaction or something more mundane," says Collar.

When a WIMP scatters the atomic nucleus and hits surrounding atoms, it could knock off electrons, therefore "ionizing" these atoms. Certain ionization detectors can measure these loose charges.

In some materials, such as liquid xenon, a light flash will indicate a WIMP. After the scattered nucleus rams into other atoms and frees electrons, the atom emits a light flash called scintillation. Usually if a detector looks for scintillation, it will also hunt for ionization.

Another approach to the direct search is using a bubble chamber — a glass jar filled with a specific type of liquid. When a WIMP hits an atomic nucleus, it will produce a tiny bubble. Scientists then watch the bubble grow. How it grows depends on whether the interacting particle was a WIMP or a background particle. A reliable WIMP detection would be if the WIMP signal varied as a result of the time of year. This is because Earth revolves around the Sun. In June, Earth's movement is in the same direction as our solar system's path around the galaxy, so the detected signal should increase. In December, Earth moves in the opposite direction, and scientists should detect a signal some 5 to 10 percent smaller. This signal difference helps distinguish the WIMPs from the background noise because the noise remains the same while the WIMP signal modulates.

The team of scientists with the DArk MAtter (DAMA) experiment claimed some years ago (and again in 2008) that it found evidence for the existence of WIMPs by looking at this modulation. Unfortunately, DAMA used only one detection method and therefore may not have been able to discriminate between background noise and a WIMP signal. And no other scientific group has repeated DAMA's discovery. In science, if another group can't repeat a finding, then there's a distinct possibility that experimental error and not evidence is responsible.

WIMPy signals

So far, direct searches haven't found WIMPs. Therefore scientists also look for the indirect signature of the dark matter candidates to complement direct searches. Neutralino annihilations should produce electrons, positrons, gamma rays, and neutrinos, along with other particles. Scientists can use certain detectors to look for each product.



The leading dark matter candidate is the theorized neutralino, the lightest weakly interacting massive particle. When two neutralinos collide, they annihilate each other and create a shower of secondary particles. Numerous detectors are looking for these secondary particles, which are therefore an indirect signature of dark matter. Astronomy: Roen Kelly



The density of neutralinos (or other WIMPs) must be high in order for these particles to meet up and destroy each other. This typically happens within more massive objects.

A WIMP near the Sun or Earth could collide with an ordinary particle's nucleus. (This is similar to what happens within detector material.) The WIMP will lose energy, and its speed could decrease below the Sun or Earth's escape velocity. If that happens, the WIMP cannot escape the massive object's gravitational hold. The WIMP can collide with another nucleus and so on until it settles into the core of either the Sun or Earth.

At the core, the densities are so high that WIMPs collide and produce secondary particles and radiation. (As mentioned before, neutrinos and gamma rays are two such products.) Several experiments underground — such as Super-Kamiokande in Japan — detect neutrinos.

WIMP collisions aren't the only nearby events that release neutrinos — the Sun produces them. Neutrino detectors can decipher WIMP neutrinos from solar neutrinos because WIMP neutrinos have greater energies. And a larger detector should find more neutrinos (hopefully of the WIMP variety). The next-generation neutrino detector IceCube should help in this search. IceCube is currently being built at the South Pole, and will cover a very large area — a cubic kilometer.

Searches for gamma rays from WIMP annihilations also look promising. The gamma rays should have a specific energy spectrum that depends on how massive the WIMP is. The Fermi Gamma-ray Space Telescope may be able to detect that particular spectrum and offer an indirect observation of dark matter. Says Hooper, "If I had to wager a guess, I would say that the best prospects to detect WIMPs in the near future are with gamma-ray telescopes." A number of ground-based gamma-ray detectors are also on the lookout.

Where's the axion?

A WIMP may be the leading CDM candidate, but it isn't the only one. The axion is also a popular possibility.

An axion detector consists of two parts: a cavity with a magnetic field and

an antenna with amplifier. According to theory, as an axion traverses the cavity, it will convert into a microwave photon. The photon's frequency will be proportional to the axion's mass. Scientists, however, aren't sure what the axion's mass is, which means they're unsure what frequency to search for. Using the antenna and amplifier, scientists will scan portions of the microwave region looking for a signal that stands out above the background noise.

Detector sensitivity is slowly getting to where it needs to be to pick out axions — and WIMPs — from background noise. It's not there yet, but scientists, with the help of elegant particle theories, are throwing everything they have at searching for (and hopefully detecting) dark matter.

"Very often in particle physics we have followed such 'natural' prescriptions, only to be surprised by nature," says Collar. With more advanced detectors coming in the next decade or so, cosmologists are sure to get a surprise — whether a hint that they're on the wrong path or a promising detection.

The search for Earth-like Worlds



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At 340 and counting, astronomers are much closer to discovering exoplanets that might resemble our own. By Geoffrey W. Marcy

or centuries, friends have gathered for lunch and conversation at outdoor cafés in northern Greece. Under the hot Sun, surrounded by appetizers and rounds of ouzo, conversations have often meandered toward the heavens, sparking heated debates about the existence of other fertile worlds. If those worlds also harbor citizens, might they also gaze toward the stars?

Such café philosophers flourished in 400 B.C., when Democritus taught his students about the possibility of other habitable worlds of great diversity and of the likelihood of life on them. Modern astrophysics is finally poised to answer the Greek philosophers' questions about other worlds and the possibility of life on those worlds. In the past 10 years, astronomers have discovered some 200 planets around nearby Sun-like stars.

New worlds found

Michel Mayor and Didier Queloz of the Observatory of Geneva in Switzerland discovered the first exoplanet orbiting a main sequence star in 1995 – a Jupiter-sized object orbiting Sun-like star 51 Pegasi. Their findings appeared in the November 23, 1995, issue of Nature. Within the next 3 months, Paul Butler and I discovered the second and third exoplanets orbiting Sun-like stars 47 Ursae Majoris and 70 Virginis, respectively, while at San Francisco State University. We reported our discovery in the June 1996 issue of the Astrophysical Journal. These discoveries gave birth to the new field of extrasolar planetary science. The parade of discoveries has continued nonstop since then.

Astronomers discovered most of the exoplanets by detecting the reflex motion of their host stars as the orbiting planets tugged them gravitationally. As the star wobbles toward us and away, its light waves alternately compress and stretch. Telescopes equipped with spectrometers that spread the starlight into its composite colors can detect this Doppler effect. However, astronomers have detected only planets the size of Jupiter or Neptune

55 CANCRI in Cancer the Crab contains a Sun-like star. In this artist's depiction of the system, we view the star from the surface of a rocky, earthlike planet. Lynette Cook

Exoplanets' mass distribution



Jupiter versus HD 149026b



Exoplanet HD 149026b

Heavy-element core

Liquid metallic hydrogen

Hydrogen and helium gas



Jupiter

SUPER-EARTH

HD 149026b has a composition similar to Jupiter's. The exoplanet's core is composed of heavy elements surrounded by a layer of liquid metallic hydrogen. Its outer layer comprises hydrogen and helium gases. Astronomy: Roen Kelly, after Geoffrey W. Marcy

Planet – metallicity correlation



ROCK AND IRON play significant roles in planet formation. Astronomers who studied 1,000 stars on their planetsearch list found a correlation between the percentage of stars with planets and the abundance of heavy elements within the stars. Astronomy: Roen Kelly, after Geoffrey W. Marcy using the Doppler method because only such giant planets have enough gravitational pull to move the stars by a detectable amount.

The giant planets found around other stars have startling properties. About 90 percent of them travel in elongated, eccentric orbits more akin to the comets in our solar system.

Another oddity is that many extrasolar giant planets — including the first ones found — orbit closer to their stars than the Earth is to the Sun (1 AU). These tight orbits defy conventional planet-formation theories in which giant planets form in the cooler, slowermoving outer reaches of a planetary system, where gas can settle gently onto rocky cores. Exactly how giant planets migrate inward and then park themselves close to their host stars remains a puzzle.

The smallest exoplanet

Improvements in Doppler technology allow us to measure stars' velocities to within 2 miles per hour (3 km/h), or human walking speed, which has permitted discovery of smaller and smaller planets. In 2005, our team detected the smallest planet yet found around a nearby star, Gliese 876: a 10th-magnitude red dwarf that is only 15 light-years away. (In April 2007, ESO found a 5 Earthmass planet around Gliese 581 in Libra.) Gliese 876 has two Jupiter-sized planets with orbital periods of 30 and 61 days locked in a gravitational resonance.

As we monitored those two Jupiter-sized exoplanets with the world's largest telescope, the Keck I in Hawaii, we were surprised the star exhibited an additional wobble not explainable by the two exoplanets. We found that a third planet of 7.5 Earth masses and a remarkably short orbital period of only 1.9 days causes the additional wobble.

Two more detection methods

Adding to the planetary parade are two marvelous new detection techniques: gravitational microlensing and transit. Gravitational microlensing occurs when light from a distant background star bends around a planet and briefly amplifies ("lenses") the star's light. Eight planets of 5 to 15 Earth masses were discovered recently by this method with orbital distances between those of Mars and Jupiter.

About 55 planets have been discovered using the transit method, during which a planet crosses in front of and dims its host star. This technique provides a direct measurement of an orbiting planet's diameter. The bigger the planet, the more starlight it blocks. Combined with the Doppler technique, which gives the masses of the planets, we can determine the planets' densities by dividing the planet's mass by its volume. Giant planets have densities near that of water, 1 gram per cubic centimeter (about the volume of a sugar cube), which is similar to Jupiter and Saturn's. Thus, most exoplanets found so far are gaseous objects.

Searching for super-Earths

The exoplanets of lowest mass point toward a new class, called super-Earths — exoplanets with masses greater than 1 but less than 14 Earth masses. Interestingly, our solar system is devoid of planets in this range. Super-Earths represent the next great terra incognita to be explored — worlds larger than Earth but smaller than Uranus. If super-Earths actually form, would they be rocky like the terrestrial planets, gaseous like Jupiter and Saturn, or icy and gaseous like Neptune and Uranus with a large rocky core? No one knows.

But observations give early clues about the existence and composition of super-Earths. Nature appears to make many more Saturn-mass planets than Jupiter-mass ones, and Neptune-mass planets seem even more abundant. Extrapolation suggests there might be yet more of the lower-mass super-Earths than all the giant planets combined.

Some known gaseous exoplanets may have rocky super-Earth cores. The best example of a likely rocky core is inside the transiting exoplanet HD 149026b, discovered by Debra Fischer of San Francisco State University. This planet has a 15 percent larger mass than Saturn but a 10 percent smaller radius. How could a planet be more massive, yet smaller in size?

HD 149026b must have an even greater concentration of rocky and iron material than Saturn. Calculations by Peter Bodenheimer and collaborators suggest the rocky core is 50 to 70 Earth masses. That whopper of a super-Earth is buried under an envelope of 30 Earth masses of hydrogen and helium and strongly suggests nature has no trouble making such enormous cores of silicates and iron. Indeed, exoplanets predominantly orbit stars rich in heavy elements, indicating rock and iron play strong roles in planet formation.

How would a super-Earth form?

Theorists have their own predictions about super-Earth formation. They predict rocky planets under 15 Earth masses form when dust particles in the protoplanetary disk clump together. As dust particles stick together and grow, like dust bunnies under your bed, the largest blobs grow faster and faster because their large sizes allow them to collide frequently with ever more dust.

These dust-and-ice blobs act like a thick ocean of "planetesimals." The largest planetesimals begin gravitationally attracting smaller planetesimals, causing large ones to grow at an accelerated rate.

Planet-formation models by Peter Goldreich, Yoram Lithwick, Re'em Sari, Scott Kenyon, and Benjamin Bromley all agree about

Geoffrey W. Marcy is a professor of astronomy at the University of California, Berkeley, and a leading exoplanet-hunter. He heads the team credited with discovering the most exoplanets.

Three planets orbiting Gliese 876



See Gliese 867d move



GLIESE 876 is depicted with three orbiting planets in this artist's rendering. The smallest of the three discovered exoplanets is 7.5 Earthmasses, one of the lowest masses of any extrasolar planet around a nearby star. Lynette Cook Inset: Gliese 876's smallest planet (Gliese 876d) has an orbital period of 1.94 days and orbits at about 15 mph (25 km/h). Geoffrey W. Marcy

the next steps. (The scientists are from Princeton, CITA, Caltech, the Smithsonian Astrophysical Observatory, and the University of Utah, respectively.) Rich planetesimals get richer and, after about 10 million years, Marssized planets form. Dozens of such planets may orbit a typical young star.

Mars-sized planets perturb each other gravitationally, causing orbits to cross and, eventually, collide with each other. Crushing upon impact, they stick and grow into Earthsized planets after some 20 to 40 million years. Glancing impacts by two such planetesimals can result in ejected magma, which can form a large moon, as presumably created our Moon.

Theory predicts protoplanetary disks that are particularly rich in silicate dust or ice particles will give birth to especially large rocky planets of 5 to 10 Earth masses. After all, why should Earth represent the largest rocky planet possible in the universe? Super-Earths must have massive iron-nickel cores compressed to somewhat higher densities, and they would have massive mantles heated by radioactive uranium, warming the interiors to tens of thousands of degrees Fahrenheit.

A fine line between ice and water

Many super-Earths will form within the disk's "ice line," located about 2 AU from the star, near our asteroid belt. The temperature within that distance is too high for ice crystals to exist. Super-Earths formed within the ice line will be composed mostly of silicates, iron, and nickel, as is Earth.

However, ice-rich asteroids could deliver water to such inner rocky planets. A Jupiterlike planet's gravity would perturb some of the hydrated asteroids into Earth-crossing orbits. The asteroids would eventually slam into the terrestrial planets and bring water to them. In this way, rocky planets could acquire various amounts of water, depending upon







NASA'S KEPLER spacecraft will search the Milky Way Galaxy for Earth-sized and smaller extrasolar planets. Kepler rocketed into space March 6, 2009. NASA



NASA'S SIM PlanetQuest spacecraft will search 2,000 nearby stars for exoplanets. (Image is not to scale.) Geoffrey W. Marcy

how perturbative the Jupiter-like planet is (due to its mass or orbital eccentricity).

Thus, some rocky planets might be nearly devoid of water — mere desert worlds without lakes, rain, or oceans. Other planets could receive 10 times, or even hundreds of times, the number of hydrated asteroids that Earth did, covering those worlds completely with a thick ocean. After all, if Earth had just twice its volume of ocean water, hardly any land would poke above sea level.

However, some planets may form beyond the ice line, in the cold outer reaches of the protoplanetary disk. There, ice particles dominate, comprising 3 times more mass than silicate dust particles. Protoplanets formed there will be composed of as much water as rock. The moons around Jupiter and Saturn are just such water worlds, albeit frozen and small. Callisto, Dione, and Enceladus are such worlds, having as much water-ice as rock. If any of those moons had migrated closer to the Sun, the added heating from sunlight would have melted them into liquid water worlds. Many Earth-mass-and-above planets located within 1 AU of their host stars may be such water worlds, with thick oceans and no continents.

Planet quest in full swing

The coming decade will see the Greek philosophers' planetary quest met with various instruments designed to detect super-Earths around Sun-like stars. NASA launched the Kepler mission March 6. Kepler is a 3-foot (1 meter) telescope with a 95-megapixel camera consisting of 42 charge-coupled devices (CCDs) to monitor 100,000 stars of roughly 12th magnitude in a field of view of 105 square degrees in Lyra and Cygnus. Kepler will monitor the stars' brightnesses with a precision of one part in 100,000 to detect dimming caused by transiting Earthsized planets. The Kepler mission will give us a statistical measure of the occurrence of planets from Earth-sized to super-Earths to Neptunesized orbiting within 2 AU of normal stars. For the first time, we may know how common other rocky worlds are.

NASA's Space Interferometry Mission (SIM) PlanetQuest is designed to detect planets of 3 Earth masses or larger that orbit stars within 20 light-years of Earth. SIM Planet-Quest will use two telescopes as an interferometer to determines a star's position with an accuracy of 1 millionth of an arcsecond.

Meanwhile, the tried-and-true Doppler technique, responsible for locating more than 200 exoplanets already, will get a boost with the completion of the "Rocky Planet Finder" Telescope at Lick Observatory. This 7.9-foot (2.4m) Hubble-sized telescope will robotically measure stars' wobbles with a precision of 2 mph (3 km/h), using a specialized, high-resolution spectrometer designed by Steve Vogt of the University of California at Santa Cruz, famous for his construction of two previous planet-hunting spectrometers.

Searching for intelligent life

One great value of nearby habitable worlds is the ability to check them for signs of intelligent life. We will use Earth's major radio and optical telescopes to search for regular, pulsing signals from our newly discovered habitable worlds; only a technological civilization could produce regular signals. We plan to use the Allen Telescope Array (ATA), the new radio telescope by the University of California, Berkeley, and the SETI Institute, for this purpose. The ATA, its construction already under way, will enable high-sensitivity monitoring of our newly discovered habitable worlds to search for radio signals from intelligent civilizations. We will also search for signals from extraterrestrial intelligence in optical and near-infrared wavelengths.

Perhaps within our lifetimes, or those of our grandchildren, we may sit at outdoor cafés along the Mediterranean neither wondering if other habitable worlds exist nor pondering if anyone lives on them. Instead, we may already know that we are not alone. If so, the lunchtime debates may focus on what constitutes "civilized" behavior in the eyes of our galactic neighbors.

A theory of rocky-planet formation

ROCKY PLANETS exhibit orderly growth through collisions of planetesimals (mile-wide comets and asteroids). Gravitational attraction focuses the planetesimals' orbits, which results in rapid growth that produces Mars-sized planets in about 10 million years. The planets eventually merge, growing to Earth's size in some 20 to 40 million years. Astronomy: Roen Kelly, after Jeffrey Bennet et al. in the Cosmic Perspective





THE ROCKY PLANET FINDER, also known as the Automated Planet Finder (APF) Telescope, is currently under construction at Lick Observatory. Extrasolar planet-hunter and University of California, Berkeley, professor Geoffrey Marcy and planet-search team member and Berkeley professor Debra Fischer stand outside the dome surveying APF's progress. Laurie Hatch

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 OUR SOLAR SYSTEM contains 4 terrestrial planets: Mercury, Venus, Earth, and Mars. Earth, the third planet from the Sun, lies within the star's habitable zone. Gas giant Jupiter lies outside it.

 SIX TERRESTRIAL planets lie in this theoretical planetary system. The second planet from its star is about Earth-sized. The giant planet, the seventh from the star, is Neptune-sized.

◄ A "WATER WORLD" terrestrial planet lies second-closest to its star in this theoretical planetary system. The huge planet has 4 times Earth's mass and 25 times the water. The planet closest to the star is dry, while the fourth, outermost planet is icy.

◄ A MASSIVE INNER terrestrial planet is the hallmark of this theoretical planetary system. The planet lies closest to its host star, followed by a "hot Jupiter," and a 3 Earth-mass planet that lies within the star's habitable zone.

DIVERSITY ABOUNDS in planetary systems both real and theoretical. In each system, the majority of terrestrial planets lies outside the star's habitable zone, a region where the temperature is right for the presence of liquid water. Astronomy: Roen Kelly, after Sean Raymond, University of Colorado

New research gives astronomers a

broad-brush view of how galaxies evolve. Now, scientists are filling in the details. /// BY RICHARD S. ELLIS



THE RING of bright knots in the center of spiral galaxy NGC 1097 is home to a recent burst of star formation, perhaps triggered by tides caused by its small companion galaxy. ESO



STAR FORMATION is so vigorous in the irregular galaxy IC 10, astronomers characterize it as a starburst galaxy. At 1.5 million light-years away, IC 10 is the nearest such system. Researchers want to understand how a modest galaxy like this forms stars so readily. LOCAL GROUP SURVEY/NOAD





MORE THAN 10,000 galaxies inhabit the Hubble Ultra Deep Field, a cosmic snapshot at the very limit of the Hubble Space Telescope's vision. In 2003 and 2004, the telescope repeatedly imaged this 3-arcminute-square patch of sky in the constellation Fornax. The result amounts to a million-second exposure. Distant galaxies look ragged, probably a result of frequent collisions.

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first galaxies

magine traveling back in time for a firsthand view of history. Astronomers come close to

having this ability. Light's finite speed means we can witness distant galaxies as they were when the universe was much younger. Astronomers now have two competing and seemingly incompatible scenarios to explain the origin of galaxies. The only way to determine which theory is right is to look back in time.

Looking back

Astronomers slice the universe into time periods defined by the redshift, a displacement in spectral features to longer wavelengths. These light fingerprints indicate how far we're looking back in time: The larger the redshift, the earlier in history we probe. The ultimate goal for extragalactic astronomers is to identify the first galaxies.

At Caltech, my recent student Dan Stark and I have used gravitational lensing — the magnification of distant galaxies by foreground galaxy clusters — to obtain a glimpse of the earliest galaxies known. What makes this feat possible are powerful cutting-edge tools: the twin 10-meter Keck telescopes in Hawaii and the Hubble and Spitzer space telescopes.

Some of the galaxies we've found lie at redshifts between 8 and 10, corresponding to 500 million years after the Big Bang. At this time, the universe was only 4 percent of its present age.

Galaxies are the universe's most visible components. In the nearby universe, galaxies come in a bewildering variety of sizes, shapes, and luminosities. Astronomers want to know how these differences arose. What physical processes shape a galaxy's destiny?

In the 1920s, Edwin Hubble at California's Mount Wilson Observatory first

Richard S. Ellis, the Steele Professor of Astronomy at the California Institute of Technology in Pasadena, California, is using the Keck, Hubble, and Spitzer telescopes to probe the nature of the earliest galaxies.

How cluster lenses magnify distant galaxies

300,000 years Redshift (z) =1,100 500 million years z = 10 2.1 billion years z = 3

recognized that the so-called spiral nebulae were not part of the Milky Way, but individual galaxies outside it. Yet serious campaigns to understand how galaxies reached their present form began in earnest only in the 1960s, when many astronomers began to predict theoretically the colors of various nearby galaxies.

Young galaxy

Elliptical galaxies contain mainly ancient red stars, whereas spirals and irregulars contain an abundance of young, short-lived, blue stars. Astronomers concluded that elliptical galaxies must have quickly transformed most of their gas into stars at an early stage. By contrast, spirals and irregulars formed stars continuously but at a more moderate pace.

This classical idea for explaining galactic characteristics assumed galaxies were isolated, self-regulated systems. But, relative to their sizes, galaxies now are closer to one another than stars are in the Milky Way. And before the universe reached its current expansion, they were even closer. Therefore, collisions should have occurred frequently.

Moreover, the old theory takes no account of dark matter. In the 1930s, Fritz Zwicky at Caltech discovered dark matter in galaxy clusters, but astronomers didn't prove its presence around individual galaxCALTECH ASTRONOMERS pioneered the use of foreground galaxy clusters as "natural telescopes" to boost faint signals from distant sources. Surveys conducted from Hawaii's Keck Observatory located several galaxies at redshifts 8 to 10. This suggests a large population of similar objects exists. *ASTRONOMY: ROEN* KELLY, AFTER J.-P. KINEIB AND R. S. ELLIS (CALTECH)

> 11.2 billion years z = 0.18

> > The gravity of a nearby galaxy cluster acts like a telescope lens.

13.7 billion years z = 0

ies until the late 1970s. We now know that most of a galaxy's mass lies outside its visible form in a dark halo. When astronomers incorporated the way gravity congregates dark matter in computer simulations, the influential "cold dark matter" picture of galaxy formation was born.

Dark matter draws together the gas that eventually fuels star formation. What we see as galaxies merely traces dark matter's presence — galaxies are just the icing on the cake. In this view, when gravity brings two dark matter halos together, their respective galaxies and gas clouds collide. The star formation rate increases, consuming and exhausting the gas supply. What's left after all this activity is an elliptical galaxy.

The contrast between the classical view and the dark-matter-dominated model could not be starker. In the former, elliptical galaxies are genuinely ancient systems, perhaps the first to have formed, whereas the dark matter picture sees ellipticals as products of recent mergers. Both may be able to explain the properties of presentday galaxies, but each is based on vastly different evolutionary histories. The only way to determine which is right is to observe what really happened.

New tools

Prior to 1993, astronomers found it difficult to get an accurate census of how distant galaxies differed from their local counterparts. Two powerful observatories changed everything: the Hubble Space Telescope, launched in 1990, and the W. M. Keck Observatory, which commissioned its first 10-meter telescope in 1993.

Fifteen years ago, the most distant normal galaxy astronomers could study lay at a redshift less than 1, which corresponds to a look-back time of some 7 billion years about halfway back to the Big Bang. With Keck and other ground-based telescopes of comparable power, astronomers now routinely study galaxies to redshift 7, when the universe was less than 1 billion years old.

Imagine scanning the crowd in a sports stadium. We easily spot the more exceptional people (say, taller or more colorful). So it is with distant galaxies. Astronomers easily spot the largest or brightest ones, but they can't be sure whether what they're seeing is extraordinary or the norm. So researchers use a variety of techniques to find different galaxy types.

The ability to study distant galaxies at different wavelengths is one of the most important advances in recent times. When

ASTRONOMERS NOW routinely study galaxies to redshift 7, when the universe was less than 1 billion years old.

we look for galaxies at large redshifts using the optical cameras aboard Hubble, we detect star-forming galaxies with an abundance of young blue stars whose ultraviolet signals become redshifted into view. Hubble is then naturally biased to see only those star-forming systems.

Star formation is destiny



SPIRAL AND IRREGULAR galaxies emit most of their light in ultraviolet and optical wavelengths, but ellipticals shine brightest in the infrared. A single, ancient burst of star formation naturally explains the colors of most ellipticals. Spirals and irregulars, on the other hand, require continuous star formation to explain their colors.

By contrast, an infrared survey using NASA's Spitzer Space Telescope, launched in 2003, can identify a different population of quiescent galaxies, ones that have stopped forming stars. Combining these approaches gives astronomers a more complete inventory. Ground-based telescopes such as Keck provide the crucial redshifts that place each of these galaxies at its correct time in cosmic history.

Revolution rising

New surveys during the past several years are driving an astronomical revolution. First came the famous Hubble Deep and Ultra Deep Fields, where the Hubble Space Telescope observed a single region of the sky to the limits of its abilities. Then, the wider-area Great Observatories Origins Deep Surveys (GOODS) united imaging and spectra from ground-based scopes with deep observations from Spitzer, Hubble, and the Chandra X-ray Observatory.

Most recently, the Cosmological Evolution Survey (COSMOS) studied an area 10 times larger than the Full Moon. COSMOS included imaging from most major spaceborne telescopes and many ground-based observatories, including the European Southern Observatory's Very Large Telescope in Chile, the Keck and Subaru telescopes in Hawaii, and the Very Large Array in New Mexico.

These massive collaborative projects have yielded unique data for millions of faint galaxies. They've also galvanized global collaborations among scientists and created special "selected areas" — sky fields studied by all major telescopes.

One result of this data explosion is improved knowledge of the universe's star formation history. According to Andrew Hopkins of the Anglo-Australian Observatory, who compiled a synthesis of recent results, star formation began at a modest rate early on. It rose to a crescendo between redshifts 2 and 3 and now is in decline.

New research also suggests the darkmatter-dominated scenario for galaxy growth is too simplistic. Yes, dark matter dominates the masses of individual galaxies, and halos can grow through mergers, but the process isn't the primary way a galaxy regulates its star formation. In the

How cold dark matter makes galaxies

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1 Dark matter halos (brown) collapse, tracing mass fluctuations emplaced during the Big Bang.

2 Gas clouds within the halos collapse and begin forming stars.

3 Gas and young stars settle into a rotating disk — a proto-spiral galaxy.

Stars form in the disk, gradually building up a true spiral galaxy.

NUMERICAL SIMULATIONS suggest galaxies grow by merging halos filled with cold, or noninteracting, dark matter. As a halo collapses, so does the gas within it. This ignites star formation. When a merger occurs, the colliding galaxies undergo a vigorous pulse of star formation, which exhausts the gas supply and leaves behind an elliptical galaxy. Recent surveys suggest this scenario explains only part of the picture. ASTRONOMY: ROEN KELLY

1980s and early 1990s, the model's champions believed dark matter's rearrangement triggered or suppressed star formation.

Big Bang

Spiral galaxy

5 One or more spirals collide with it, expelling gas or consuming it in vigorous star formation.

Galaxies downsized

The main challenge to the dark-matterdriven scenario comes chiefly from observations that show many massive galaxies ended their growth and star formation at high redshift, while lower-mass systems continue to add new stars to the present day. This "downsizing," as Len Cowie and his colleagues at the University of Hawaii call it, contradicts a picture in which dark matter halos grow progressively from smaller units into larger ones. Other physical processes must govern how galaxies convert gas into stars. What can they be?

A 2006 survey led by Caltech graduate student Kevin Bundy, now at the University of California at Berkeley, gives us perhaps the clearest view yet of how downsizing occurred over the past 8 billion years. Bundy and his colleagues tracked the distribution of stellar masses in more than 8,000 galaxies with various star formation characteristics out to redshift 1.5. Galaxies appear to form new stars until they reach some critical-mass threshold. After that, star formation ends, and the system matures into a red elliptical. Lower-mass galaxies, which make stars at a much slower rate, never reach the cutoff point. Why do galaxies stop growing? Astronomers are hunting for feedback processes that could inhibit star formation. Perhaps some agent expels gas and shuts down the process. Or maybe gas simply becomes so hot that it can't efficiently cool to collapse into stars. Theorists Darren Croton of the Swinburne University of Technology in Australia and Richard Bower of Durham University in the United Kingdom suspect the cutoff may be linked to the supermassive black holes found in the centers of most galaxies.

In nearby galaxies, astronomers find a close relationship between a galaxy's mass and the size of its black hole: the bigger the galaxy, the more massive the black hole. Black holes can be dormant, as in our Milky Way, or active, as in galaxies with prominent X-ray emission and energetic jets. Several groups now are using X-ray data from Chandra to test the idea that black holes govern star formation in a galaxy. They're attempting to explain downsizing trends by determining which galaxies have active black holes at various times.

When did spirals spiral?

Nearby galaxies show different dynamical properties. Our Milky Way, a spiral galaxy, contains a rotating stellar disk. An elliptical galaxy, on the other hand, is basically a ball of stars, each of which follows a random orbit. To understand a galaxy's internal dynamics, we need detailed spectra from different parts of the galaxy. That's quite a challenge at great distances. A galaxy at redshift 2, for example, has an angular diameter of only 1" to 2". From a typical ground-based observatory, Earth's atmosphere would blur any rotation pattern.

Fortunately, several major telescopes boast another innovation, called adaptive optics, that overcomes this difficulty. With a perfect correction, a 10-meter telescope could attain a resolution of 0.05" at nearinfrared wavelengths. This corresponds to details as small as 1,000 light-years for a galaxy at redshift 2! While adaptive optics systems usually don't perform this well in practice, groups led by Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics in Munich) and Chuck Steidel

Star formation through time



NEW RESEARCH gives astronomers a census of the universe's star formation history. Activity peaked between 10 and 11 billion years ago. The universe now forms stars at 10 percent of the rate it did 7 billion years ago. *Astronomy:* ROEN KELLY, AFTER A. M. HOPKINS AND J. F. BEACOM, 2006

coupled with adaptive optics, TMT will provide details on physically small sources.

The faint sources Dan Stark and I found using gravitational lensing are, indeed, physically small — only 1,000 light-years across. Tha's 50 to 100 times smaller than the Milky Way. There seem to be a lot of them, and their collective energy output could represent a significant fraction of the energy needed for cosmic ionization.

We're working now to verify this, but we've almost reached the limits of current astronomical facilities. More detailed studies of the most remote galaxies currently known may simply have to wait for new facilities like JWST and TMT.

Hubble, Spitzer, and Keck enable us to see how galaxies developed from small, immature systems into the majestic forms Edwin Hubble classified in the 1920s. The theory underpinning galaxy growth has made great strides, too, even if the details of how galaxies regulate their star formation remain unclear. We now look to the final frontier, peering back to an era before galaxies formed.

Edwin Hubble understood both our motivations and our challenges. "At the last dim horizon," he said, "we search among ghostly errors of observations for landmarks that are scarcely more substantial. The search will continue. The urge is older than history. It is not satisfied and it will not be oppressed."

Elliptical galaxy

6 The merger's product is an elliptical galaxy.

(Caltech) have achieved major resolution gains. Their results suggest that many distant galaxies have yet to reach the dynamical maturity we see locally.

Astronomers hope to uncover an evolutionary trend as more teams use the remarkable power of adaptive optics. Among other things, we'd like to know when the rotating disks we see in all present-day spirals became established.

Final frontier

For astronomers interested in galaxy evolution, baby galaxies — those that formed only a few hundred million years after the Big Bang — mark the final frontier. The search for the first galaxies, which astronomers believe formed when the universe was less than 5 percent of its present age, now drives the design of new telescopes.

Some 300,000 years after the Big Bang, hydrogen gas clouds formed. Gravity from dark matter clumps gathered and compressed the clouds, which collapsed and formed the first stars. These pristine systems contained only the nuclei of the simplest atoms, hydrogen and helium, forged in the Big Bang.

Theorists like Tom Abel at Stanford University believe these first stars were short-lived and massive. They shone briefly at redshifts of 20 to 50, long before the wholesale formation of small galaxies at redshifts 10 to 20. This first stellar generation may have been numerous and energetic, so much so that the stars' ultraviolet light escaped and affected cold hydrogen in deep space. This radiation stripped electrons from hydrogen atoms, ionizing them.

Only after this event could visible light traverse intergalactic space. Needless to say, observing when this landmark event occurred, and characterizing the sources responsible for it, excites astronomers.

For galaxies at redshifts beyond 7 a distance corresponding to 900 million years or less after the Big Bang — cosmic expansion shifts most of their light into infrared wavelengths. This is a particularly challenging region of the spectrum for

THE FAINT SOURCES found through gravitational lensing are up to 100 times smaller than the Milky Way.

ground-based observations. Ultimately, future facilities such as NASA's James Webb Space Telescope (JWST) — a 6.5-meter successor to Hubble — will reach much deeper. The observatory, slated for launch in 2014, is optimized for infrared work.

A few years later, if all goes according to plan, a new ground-based observatory called the Thirty Meter Telescope (TMT) will complement JWST. With a mirror 3 times the size of the Keck telescopes and



Infinitely long, exceedingly thin, and unimaginably dense strands of primordial matter may wind their way through the universe. /// BY STEVE NADIS

osmic strings have led a checkered past: popular in the 1980s, denounced in the 1990s. Now, theoretical revisions support the idea that ultradense strands of matter could be the "seeds" for galaxy formation. Even Edward Witten of the Institute for Advanced Study, widely recognized as one of the world's greatest theoretical physicists, now believes "strings of different sizes and kinds probably exist" — despite the fact that, 20 years ago, Witten argued convincingly none was to be found. So, why are scientists now getting wound up about cosmic strings?

Much of the impetus comes from revisions to string theory, which describes fundamental forces and particles as tiny, string-like loops of energy. Current versions of the theory show strings — the basic units of energy and matter — can reach astronomical sizes.

These strings, argues Joseph Polchinski from the University of California, Santa Barbara, would have been produced after inflation, which otherwise would dilute them to oblivion. Reformulated cosmic strings are stable over the age of the universe and less massive than the strings Witten and others contemplated in the 1980s. This means their influence on the universe would be less dramatic than previously thought, so they can't be ruled out by recent observations.

Defects in space

Witten concedes Polchinski and his colleagues deftly address the difficulties he raised, yet one question remains: Can we detect cosmic strings?

Maybe. Two research teams report evidence for cosmic strings in different parts of the sky. While these claims have yet to be either verified or refuted, they have "breathed new life into this field," says Alexander Vilenkin of Tufts University, who in the 1980s first suggested cosmic strings could trigger galaxy formation.

Cosmic strings are second only to black holes in the astrophysicist's zoo of weird objects. They are narrow, ultradense filaments formed during a phase transition — called inflation — within the first microsecond of cosmic history. Just as cracks can appear in ice as water changes from liquid to solid, the universe could have developed topological defects as it inflated. Linear defects would have formed at junctures where different areas undergoing the transition ran into each other, leaving behind slender threads of unconverted material forever trapped in a primordial state.

Cosmic strings, the theory says, emerged from this phase transition in a spaghetti-like tangle. Individual threads move at significant fractions of the speed of light.

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ONCE CONSIGNED to cosmology's trash bin, cosmic strings have returned with a vengeance. Because a cosmic string acts like a cylindrical gravitational lens, astronomers may be able to trace a string's location by looking for pairs of identical galaxies. In one intriguing case, some researchers think they've found one. LYNETTE COOK FOR ASTRONOMY 21



WHEN STRINGS COLLIDE, they can exchange pieces and form a free-floating loop. In this computer simulation, two strings approach one another at half the speed of light, emitting radiation — usually gravitational waves. A new loop forms in the collision's aftermath.

They're either long and curvy, with a complex assortment of wiggles, or fragmented into smaller loops that resemble taut rubber bands.

Although thinner than subatomic particles, cosmic strings are boundless in length, stretched by cosmic expansion across the universe. They are physically characterized by their mass per unit length, or tension, a parameter that reflects their gravitational heft. This linear density can reach incredibly high values — about 1 million metric megatons per centimeter for strings formed at the so-called grand unification energies (10¹⁶ billion electron volts and higher), corresponding to a time when all four fundamental forces in nature were combined as one.

Steve Nadis is a science writer and frequent Astronomy contributor who lives in Cambridge, Massachusetts. "Neutron stars are among the densest compact objects we know of, but even if we squeezed one billion neutron stars into the size of an electron, we would still hardly reach the matter-energy density characteristic of grand unified cosmic strings," notes Alejandro Gangui, an astronomer at the University of Buenos Aires.

String lenses?

Objects this massive must have a phenomenal gravitational influence. If a string ran between the Milky Way and another galaxy, light from that galaxy would go around the string symmetrically, producing two identical images near each other in the sky.

"Normally you'd expect three images, if lensing is due to a galaxy," says Vilenkin, with some light traveling straight through the lensing galaxy and other rays traveling around either side. Light can't go through a

THE DOUBLE QUASAR

In 1979, radio astronomers found the Double Quasar, Q0957+561A/B, in Ursa Major. A foreground galaxy cluster creates two identical images of the same quasar separated by 5.7". This was the first confirmed gravitational lens, and it has played a pivotal role in astronomers' understanding of the phenomenon.

In August 2004, a team led by Rudolph Schild of the Harvard-Smithsonian Center for Astrophysics detected concurrent brightness changes in both quasar images. Looking at data from 1994 and 1995, the astronomers found several oscillations with a period of about 80 days. If these changes have a common origin, the astronomers reasoned, they must be due to a large object very close to us.

Schild and colleagues calculated a binary pair of 78-solar-mass stars within 4 light-years of Earth could cause the effect. But the idea that such stars would have



A MASSIVE GALAXY splits the distant quasar's light and forms two images.

gone unnoticed seems unlikely — and the mass requirement only increases for more distant objects.

On the other hand, a cosmic string loop within our galaxy could produce the fast oscillations. A period of 80 days implies a loop about 160 light-days long. Trucking through our galaxy at a substantial fraction of light-speed, the loop might spend only a year in the line of sight between Earth and the Double Quasar. — *Francis Reddy* string because the string's diameter is much smaller than the light's wavelength, so strings produce only two images.

A Russian-Italian group led by Mikhail Sazhin of Moscow State University has recently discovered remarkably similar double images of a galaxy named CSL-1 in the constellation Corvus. Both images have the same redshift (0.46), and their spectra are "identical at a 99.96-percent confidence level," claims Giuseppe Longo, a collaborator from Federico II University in Naples. The data "can be interpreted either as the chance alignment of two identical galaxies," the Italian team says, "or as the first case of lensing by a cosmic string."

Vilenkin considers this observation an "intriguing case that a string could explain quite naturally." Thomas Kibble of Imperial College in London, whose 1976 paper sparked interest in cosmic strings, thinks there's a reasonable chance a cosmic string is responsible for the images. "I won't bet heavily on it, but I might make a small wager," he says.

There's nothing uncommon about finding pairs of galaxies in the sky, counters Harvard University cosmologist Abraham Loeb: "Andromeda and the Milky Way are close together, and, to a distant observer, they might look very similar."

There's no way to exclude the possibility of two similar galaxies sitting next to each other by coincidence, agrees Case Western Reserve physicist Tanmay Vachaspati. If there is a cosmic string there, he says, the number of double images in its vicinity should exceed that expected by chance. Sure enough, Sazhin and colleagues found 11 other pairs in the area around CSL-1. Their next step is to obtain more detailed spectroscopy with the European Southern Observatory's Very Large Telescope in Chile to find out how similar these paired galaxies really are.

The team also is pursuing another, possibly more definitive, test: trying to determine whether the images are truly identical or just vaguely similar. Lensing by a galaxy leads to



▶ WHEN COSMOLOGISTS MODEL cosmic-string evolution, their main goal is to predict how a number of averaged properties — such as the speed, separation, and number of strings in a given volume change over time. The simulation at right shows strings when the universe was young and dominated by radiation, in its first 10,000 years. Space is filled with cosmic strings. Long strings have many "wiggles," and there's a high density of small string loops.

distorted images that differ in size and shape — light passing far from the galaxy appears to bend less than light passing nearby. A cosmic string bends light by the same amount no matter how far light passes from it. So, if the string is straight, it will produce two undistorted images with a sharp edge between them — like a pair of snapshots sitting side by side. "No other phenomenon to our knowledge can produce such a morphology," says Longo. If the astronomers see a sharp edge with the Hubble Space Telescope, the only instrument with sufficient angular resolution, they'll be confident it is a string.

Meanwhile, there may be another cosmic string floating around our galactic neighborhood. The idea — postulated by Rudolph Schild of the Harvard-Smithsonian Center

A BILLION NEUTRON STARS crushed to an electron's size wouldn't match cosmic-string densities.

for Astrophysics and three colleagues from Kiev Observatory — is that brightness oscillations in a well-known quasar, Q0957+561A/B, are explained most plausibly by a cosmic string loop located within our galaxy's halo.

Monitored since 1979, Q0957 is the firstknown example of gravitational lensing. A distant galaxy serves as the lens, which creates two images of the quasar that show the same brightness oscillations, although separated by a 1.1-year time delay. But during



a 400-day period in 1994 and 1995, the brightness of the two images oscillated in synch, with no time lag. Schild and company attribute this anomaly to a gravitational lens. They think a rotating string loop flew across our line of sight in 1994 and 1995, simultaneously affecting both quasar images. More conventional explanations, such as lensing by a double-star system, already have been ruled out.

Fermilab physicist Mark Jackson finds the explanation interesting, but inconclusive. "We need a more sophisticated [cosmic string] model to see if it holds together," he says.

Finding a nearby cosmic string — estimated at 10,000 light-years away — is highly unlikely, although not impossible, says Vachaspati. Computer simulations suggest long strings should be spaced roughly 325 million light-years apart. But for now, he doesn't have a better explanation for the synchronous blinking.

What's needed, says Tufts physicist Ken Olum, is a statistical analysis that would reveal whether the unexpected brightness



A SNAPSHOT OF A STRING NETWORK

in the universe's matter-dominated era after the first 10,000 years — shows a much-lower density of both long strings and loops. Also, long strings display fewer wiggles. Simulations of string evolution help cosmologists test how effectively cosmic strings can trigger galaxy formation.

fluctuations are, in fact, real. Schild concurs and is working on that problem with Bell Labs mathematician Dave Thomson.

Confirmation of just one lensing event by a cosmic string would be momentous. Researchers can estimate the string's tension by determining the extent to which light is bent. The tension, in turn, reflects the energy scale of the primordial phase transition that gave rise to the string. Knowing this energy scale would help cosmologists limit possible models of the early universe.

With one lensed pair in hand, investigators will try to trace out the string's path in the sky. "The string will cut through the middle of the two objects, but the angle is hard to determine," explains Vachaspati. Most likely, the search will be hit-or-miss at first, as astronomers scour the surrounding area. But as more pairs are found, the path of the string should become clearer. "You can search in optical, infrared, radio, whatever you like," says University of California, Berkeley, astrophysicist George Smoot. "A cosmic string would treat all light alike."

STRING SPEAK

COSMIC STRING

A hypothesized defect in space-time created when the universe cooled.

GRAVITATIONAL LENS

A massive object, such as a group of galaxies, that warps space and alters the path of radiation passing near it.

GRAVITATIONAL WAVE

A propagating gravitational field produced by some change in the distribution of matter. Predicted by Einstein, gravitational waves travel at the speed of light, exerting forces on masses in their paths.

SPACE-TIME

A combination of all spatial dimensions and time.

QUASAR

The brilliant core of a distant galaxy, thought to be powered by a supermassive black hole.

Once there's an unambiguous case of lensing by a string, Polchinski adds, "We'll want to do a systematic search." He predicts the science will move quickly after astronomers verify the first discovery. "We're likely to go from one event to 1,000 events in 10 years." While this survey proceeds, people will continue to invent new ways of looking for strings. The cosmic microwave background (CMB), for example, offers another avenue. Cornell University physicist Henry Tye suggests cosmic strings may be responsible for 10 percent of the temperature differences (and related density fluctuations) in the CMB, thereby contributing to the creation of galaxies and galaxy clusters. Smoot says he and other researchers are waiting for better data to pin down what, if any, role strings played in structure formation.

Even if a supporting role is ultimately ruled out, cosmic strings should still create a linear discontinuity in the CMB — two regions with slightly different temperatures. This temperature difference stems from the Doppler effect: Photons on one side of the fast-moving string get pushed, which gives them a higher frequency and temperature than photons on the other side that are not pushed. Although this effect has not yet been documented in CMB data, it may be detectable, says Tye, depending on how fast the string is moving and its tension or mass.

Looking with LIGO and LISA

Long threads of superdense material moving near the speed of light should

throw off lots of gravitational radiation — an effect predicted by Albert Einstein almost 90 years ago. The Laser Interferometer Gravitational-wave Observatories (LIGO) in Louisiana and Washington might be able to detect such a disturbance. Vilenkin, who first considered gravitational radiation from strings in 1982, says, "This may be the only source of gravitational waves LIGO could detect."

The most visible signal would be produced by a cusp — a transient spike that forms when wiggles traveling along a cosmic string in opposite directions momentarily meet. As the cusp straightens itself out, its tip moves at the speed of light. "Like the crack of a whip, a great deal of energy is concentrated in the tip," Polchinski notes, "so it emits an intense beam of gravitational waves in the direction of its motion."

Cusps are the easiest thing LIGO could spot, says LIGO team member Xavier Siemens of the University of Wisconsin, Milwaukee. Such a signal is within reach of the current LIGO, says Siemens, and it should be even more prominent when the "advanced" version comes online in a few years. With its greater sensitivity, the Laser

CAPODIMONTE STERNBERG LENS CANDIDATE 1 (CSL-1)

Images produced by garden-variety gravitational lenses — foreground galaxies or galaxy clusters — typically come in odd numbers and differ significantly in brightness. Cosmic strings should act as cylindrical gravitational lenses, creating nearly identical double images of any sources behind the strings.

In 2003, collaboration between Capodimonte Observatory in Naples, Italy, and Sternberg Astronomical Institute at Moscow State University turned up a close pair of seemingly similar elliptical galaxies in Corvus. Now known as Capodimonte Sternberg Lens candidate 1 (CSL-1), the galaxies appear to be twins separated by 2". If the pairing is a coincidence, it's a remarkable one, and there's no sign of a giant foreground galaxy that might serve as a traditional lens. A team led by Moscow State's Mikhail Sazhin concluded the best explanation was lensing by a cosmic string.

The same team then searched for pairs among the roughly 2,200 galaxies near CSL-1. The astronomers found 11 pairs that, on the basis of separation and color similarity, could be lensed galaxies. Conventional lensing, they argued, should produce no more than two pairs in the same field of view, while a cosmic string could produce as many as 200, depending on its precise configuration.

A cosmic string should leave its distorting imprint on the CMB. Using Wilkinson Microwave Anisotropy Probe data, astronomers Amy Lo and Ned Wright of the University of California, Los Angeles, searched for and found an edge in the microwave background at CSL-1. But if the edge is real, a



CSL-1 (inset) and other paired galaxies (light blue) may trace a cosmic string.

cosmic string responsible for it must be moving at more than 96 percent of lightspeed — unlikely, they conclude. Critical tests of CSL-1 must await detailed data from facilities now being built, such as the European Space Agency's Planck probe. — F. R.



Interferometer Space Antenna (LISA), due to be launched next decade, would have a better chance of intercepting a cusp signal.

Because a cosmic string is a piece of the universe from a more energetic state, it provides a unique view of the physics that prevailed when it was created. "Cosmic strings might actually provide the best observational window into fundamental string theory," notes Imperial College's Thomas Kibble, while also offering the chance to test the predictions of stringbased inflation models.

Most of those models are now based on "brane inflation," an idea advanced by Tye and New York University physicist Gia Dvali in 1999. Inflation, they suggest, ensued when two stacks of three-dimensional membranes, or branes, drifted toward each other in higher dimensions due to gravity's tug. In this scenario, inflation ended when the branes collided and melted, creating the Big Bang.

Polchinski likes the Dvali-Tye scenario because it shows where the energy that drives inflation comes from. "Brane inflation offers a natural geometric picture that automatically leads to the right phase transition that produces cosmic strings," he says.

Two kinds of cosmic strings were created during that phase transition, according to Tye: F-strings, the basic building blocks of string theory that make up electrons and protons, stretched across the entire sky; and D-branes, which assume various forms, including one-dimensional strings. "Brane inflation gives you all you need for cosmic strings to survive and be observable," says Dvali. What's more, adds Tye, string tensions predicted by brane inflation are compatible with the latest observations.

How would these cosmic strings differ from the "old-fashioned" ones discussed by Kibble and Vilenkin in the 1970s and 1980s, before string theory took off? To simplify the terminology, some researchers use the term *cosmic superstrings* to distinguish new stringtheory versions from the cosmic strings of old. "Every idea that existed for conventional cosmic strings has a counterpart in string theory," says Fermilab's Mark Jackson. But



COSMIC STRINGS FORMED as defects in space-time when the universe cooled. The process is analogous to cracks that form as water freezes to ice.

the concept is much richer because it predicts a greater variety of superstrings.

Superstrings travel in different dimensions and have a range of tensions, whereas scientists expect traditional cosmic strings have uniform tensions. In string theory, three different cosmic superstrings can join to form a junction, and each would have a different tension that fits a specific

COSMIC STRINGS OFFER a glimpse of physics at energies far greater than accelerators can reach.

relationship, says Jackson. The old kind of cosmic strings don't form junctions.

What happens when strings collide also differentiates them. Cosmic strings almost invariably reconnect, meaning the two strings intersect to form an X. The X, in turn, breaks off to form two Vs. The Vs become vibrating loops that decay through gravitational radiation and eventually disappear. Cosmic superstrings, by contrast, don't always reconnect; they can pass through each other without crossing because they move in higher dimensions.

The difference should have significant observational consequences. There should be more long cosmic superstrings around than cosmic strings simply because superstrings cut themselves up less often. "By looking at the sky and counting the number of long strings, we may be able to tell whether they are ordinary cosmic strings or superstrings," says Vilenkin.

A cosmic-string "census" would be helpful in this regard, but for the time being, such an effort will have to be accomplished with a computer rather than a telescope. Simulating the distribution of cosmic strings is exceedingly difficult, says Polchinski, in part because of the dynamic range: from loops on the light-year scale to long strings extending 10 billion light-years or more. Plus, the system itself is intrinsically complex to model, with long strings and smaller loops moving, crossing, and oscillating in nonlinear ways - all occuring in an expanding universe. Although detailed computer simulations could help scientists predict how strings are arranged in the sky, it may take a credible detection before researchers take on such a project.

Vilenkin, along with Tufts colleagues Ken Olum and Vitaly Vanchurin, is developing a simulation to determine the curviness of strings and the number and size of their wiggles and loops — all of which affect the gravitational waves likely to be produced. A major undertaking, it could provide insights on cosmic-string evolution, which remains poorly understood.

Knowledge gained from simulations, theory, and observations offers a large potential payoff. "This will be a window on physics at energies up to a trillion times higher than particle accelerators can reach," Polchinski says. "We're really at the dawn of a new era of science."

And cosmic strings, which not long ago seemed destined for the rubbish bin of physics, are now center stage. Well, maybe not exactly at the center: They may be lurking, instead, at our galaxy's edge.

Unveiling the

A new ground-based telescope promises to nail down the distribution of dark matter. /// BY RAY VILLARD

Virtually all our understanding of the universe is built on "pedestals of light," the bright objects that fill the night sky. Yet the glow of gas, stars, and galaxies has skewed our view of the universe in much the same way that someone flying at night can only guess at the topography of the ground below from seeing the lights of towns and cities.

Astronomers now realize those light pedestals are embedded in an invisible fabric called dark matter, which accounts for nearly one fourth of all the stuff in the universe. Add to that the even stranger realization that a repulsive form of gravity (or antigravity), dubbed dark energy, may be pushing galaxies apart while accounting for nearly three quarters of the universe's energy content. Visible light comes from ordinary matter, which makes up only about 4 percent of the universe's total mass-energy content. Simply put, there's a lot out there we can't see.

Despite the exquisite resolution of the Hubble Space Telescope or the sensitivity of the twin Keck telescopes, today's powerful observatories can barely scratch the surface when it comes to probing this unseen universe. For centuries, starlight was virtually the only game in astronomy, but it's now clear we'll never fathom the architecture of the universe by studying starlight alone.

This calls for an innovative and radically new dark-matter probe — the proposed Large-aperture Synoptic Survey Telescope (LSST). The LSST won't look for dark matter particles directly — whatever they are — but it will infer the presence of dark matter by a phenomenon called gravitational lensing. Scientists will be able to calculate the mass and distribution of dark matter by seeing how it deflects light emitted by luminous objects.

The LSST is a follow-on to the highly successful Sloan Digital Sky Survey, which ultimately will map one-quarter of the entire sky, determining the positions and brightnesses of more than 100 million celestial objects and distances to more than a million galaxies and quasars. The LSST will

DARK MATTER PERVADES THE UNIVERSE, as in galaxy cluster Abell 2218, where its gravity distorts the light of more distant objects. The LSST will map the distribution of dark matter in the universe in unprecedented detail. NASA, ESA, ANDREW FRUCHTER (STSCI), AND THE ERO TEAM (STSCI + ST-ECF)

Updated from the November 2002 issue of Astronomy

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UNIVERSE



THE NATIONAL OPTICAL ASTRONOMY OBSERVATORY'S DEEP LENS SURVEY shows incredible detail, but it will pale in comparison with what the Largeaperture Synoptic Survey Telescope has in store. DEEP LENS SURVEY AND NOAD

also complement other proposed cosmology missions such as the Supernova Acceleration Probe (SNAP). Veteran dark-matter sleuth Tony Tyson of Bell Laboratories/Lucent Technologies and master mirror-maker Roger Angel of the University of Arizona are part of the team of astronomers and physicists trying to achieve "first light" for the new observatory by 2011.

The telescope they're lobbying for will be a powerful and versatile instrument that will do what a few years ago would have been deemed impossible — map almost the entire sky down to 24th magnitude every several nights. That's a threshold so faint that the nightly inventory will number 200 million objects.

"There will be about 30,000 galaxies and 3,000 stars per square degree of sky — not counting tens of thousands of asteroids," says Tyson. "We will repeat these exposures at least every 25 seconds through the night, tiling the sky with 7-square-degree patches."

Over a significant amount of time, a total of 14,000 square degrees will be covered with multiple exposures to build an image down to 27th magnitude, which corresponds to 600,000 galaxies per square degree. The resulting image compilation and photometric catalogs will contain roughly 10 billion objects: galaxies, stars, brown dwarfs, comets, asteroids, and energetic explosions in the early universe.

This will allow the LSST to map out the huge dark-matter structures that form a ghostly cobweb across the universe. Acting as a movie camera, it will document key phenomena in a transient universe — one crackling, popping, and bubbling with titanic explosions, stellar flares, and other outbursts.

Closer to home, the LSST will also keep tabs on the solar system's silent denizens of the night. It will chart the orbits of almost all

Ray Villard is public information officer at the Space Telescope Science Institute in Baltimore, Maryland. asteroids and comets that pose a threat to Earth. The LSST will do a census of the Kuiper Belt, the solar system's last unexplored frontier.

The huge "discovery space" available to the LSST — only marginally accessible to today's telescopes — is guaranteed to make deep inroads into everything from probing the underpinning of the universe's origin and evolution to doing a complete inventory of our solar system. When opening a vast frontier like this, it's a sure bet the telescope will deliver profound and unexpected discoveries that reinforce the emerging view that the universe is a far stranger place than we ever imagined.

Big job, big scope

The telescope needed to accomplish such a herculean task must be herculean too. It requires an innovative optical design, a stateof-the-art "supercamera," and an extremely ambitious computer system to sort and archive the flood of data that will exceed the volume of everything collected by the present generation of telescopes put together.

The LSST's wide field of view requires a short 10-meter focal length. The center of gravity is in the middle of the squat telescope so it can quickly pivot around a small turning radius inside a relatively small housing. To control the wide view, the telescope has three sets of mirrors. The large 8.4-meter primary mirror is a twin of the mirrors on the University of Arizona's Large Binocular Telescope.

Relative to other 8-meter-class telescopes, the LSST will be like a motor-driven handheld camera compared with a portrait-studio, tripod-mounted camera. To survey the sky, the telescope has to be agile enough to re-point by 3 degrees in merely five seconds.

The novel optical design will allow LSST to go very deep and wide. The telescope will gaze at a whopping 4,000 square degrees of sky per night, approximately one hundred times the area of the bowl of the Big Dipper.



THE LSST WILL DETECT THOUSANDS OF DISTANT SUPERNOVAE like this one (arrow) in the Hubble Deep Field, helping to pin down the accelerating expansion rate of the universe. NASA AND ADAM RIESS [STScl]

The LSST will need to be located at a prime ground-observing site with the best possible weather. A site in the mountains of Chile is under consideration. Ideally, a telescope in the Northern Hemisphere could combine with one in the Southern Hemisphere to cover the entire celestial sphere. Being on the ground rather than in space will keep construction costs to approximately \$120 million, although seeing conditions will not be as optimal.

In a 20-second snapshot, the fast optics will plunge deep into the cosmos to capture faint stars and galaxies the size of our Milky Way located halfway across the universe.

The tertiary mirror will feed starlight from its 3°-wide field of view to a 2-foot mosaic of dozens of optical detectors totaling 2 gigapixels. Starting a new exposure of a different part of the sky every 30 seconds, the LSST's camera will pour out imaging data at 500 megabytes per second. The torrent of data from the LSST is unprecedented for any current optical telescope but comparable to the data rates found in particle physics experiments.

Software must process the data stream in close to real time in order to automatically detect and classify both variable and moving objects. Results will be placed in an archive that can be readily retrieved by the astronomical community.

Mapping the shadow universe

Despite today's vast array of magnificent ground- and spacebased telescopes, it is humbling to realize we can't see the very substance that dominates the mass of the universe and controls the development of its structure. Over billions of years, and working in ways no one truly understands, dark matter established the underlying foundation for assembling ordinary matter into galaxies, stars, planets, and life.

The gravitational effects of dark matter give the universe a distorted "shower curtain" appearance caused by gravitational lensing. Albert Einstein first predicted this phenomenon when he theorized that gravity warps space. This means light can be deflected by gravity as it crosses space, like a golf ball rolling over uneven turf.

But you really don't appreciate how distorting a transparent shower curtain can be until someone stands behind it and you see how much the person's appearance changes. Likewise, the light from billions of distant galaxies provides background wallpaper that is noticeably distorted by dark matter in the foreground. The LSST will need optimum observing conditions to measure the "shear effect" on galaxies, a measure of how much their images are stretched by lensing.

The LSST will make a three-dimensional map of this dark matter by measuring distances to both the gravitationally lensed galaxies and the foreground clusters of mass that are doing the lensing. Distances to the background galaxies will be measured based on their color. This technique, called photometric redshift, is used increasingly as a substitute for the traditional spectroscopy that makes an unequivocal measurement of an object's cosmological redshift. But many distant targets are simply too faint for this tried-and-true technique to be used exclusively anymore.

The LSST's mapping of dark matter will measure both the geometry of the universe and the growth rate of its structure. The amount of distortion in the shapes of galaxies will help fine-tune the measure of the universe's balance of energy and matter. Dark energy inhibits the growth of structure, so the LSST will help determine the nature of the elusive dark energy that is now pushing the universe apart.

The mapping will also identify galaxy clusters at great distances and tell us how quickly large-scale structures froze out of the darkmatter web in the early universe. Gravitational lensing can also split images of distant quasars, and the frequency of this effect yields clues as to how gravity curves space.



THE LSST WILL EXCEL AT FINDING OBJECTS that flare up in the darkness of space, as this gamma-ray burst (arrow) did in January 2000, when it surged energy into deep space. ESO

The LSST can play a role in probing dark energy — the dominant component of the universe's energy density — by searching for supernovae. Supernovae present a window into the distant past and offer the best way to measure how the universe's expansion has changed over time.

Hubble Space Telescope astronomers got lucky in 2000 with their chance discovery of a distant supernova. It was so far away that it yielded the long-awaited evidence that the universe once was slowing down but is now speeding up thanks to the repulsive influence of dark energy.

If the universe were expanding at a steady rate, the light from distant supernovae would dim at a predictable pace depending on their distance from Earth. If the supernova light is brighter than predicted, the universe has been expanding slower than expected since the time the supernova exploded. If the light is fainter than predicted, the universe has been expanding faster than expected since the time the supernova exploded.

But many more remote supernovae must be found to help astronomers understand the nature of the dark energy that kicked the universe into high gear 7 billion or so years ago. Ground-based surveys have netted fewer than 300 supernovae per year. The LSST will complement the ambitious supernova survey planned by the proposed SNAP mission that is expected to find more than 1,000 supernovae at the critical epoch when cosmic acceleration began. SNAP will provide a deep "pencil-beam" view of the sky; the LSST's designers predict that LSST's wide view and depth will capture 200,000 moderately distant supernovae each year. By training their eyes on supernovae, LSST astronomers hope to determine the exact amount of expansive push dark energy exerts as compared to the exact amount of gravitational resistance provided by dark matter.

The LSST will also open a new window into the early, violent



ASTRONOMERS HAVE DISCOVERED about 1,000 Kuiper Belt Objects, including the round smudge of 1996 TO_{66} seen here. The LSST should find at least 10,000 of these distant solar system objects. ESO

universe. Far away and long ago, galaxies collided more frequently than now and stars were born in firestorms of creation triggered by those collisions. Astronomers started getting hints of this violence in the 1970s, when defense satellites led to the discovery of gamma-ray bursts (GRBs). Unleashing 100 times the power of a supernova, these titanic gamma-ray explosions happen about once per day somewhere in the sky. Most sources reside billions of lightyears away. With luck, the telescope's wide view will pick up fainter GRBs popping off like firecrackers. The telescope will record their color and precise brightness and track their fading afterglows.

What's new?

GRBs form just the tip of the iceberg. A staggering variety of astronomical phenomena come and go like fireflies in the night. Collectively called transient events, they include outbursts from black holes powering active galaxies and quasars, variable stars, stellar flares, and microlensing events where a star momentarily brightens when a dim foreground object passes in front of it.

The LSST promises to yield new insights into our own galaxy by compiling a huge database of variable stars of many types, such as eclipsing binaries. There is a tantalizing opportunity to find extrasolar planets by witnessing rare transit events, where a planet tracks across the face of its parent star. Astronomers also anticipate the LSST will turn up previously unknown objects and phenomena.

The LSST's wide field and sensitivity are not just for perusing the distant universe. Much closer to home, at the frigid, outer fringes of our solar system, perhaps billions of faint small bodies travel the dim highways of the Kuiper Belt. Discovery of inhabitants in this vast, icy, debris yard beyond Neptune has climbed rapidly in the past few years. About 1,000 of these Kuiper Belt Objects (KBOs) have been found so far, including a new population of



THE LSST WILL COMPLETE THE SURVEY of near-Earth objects larger than a football field across. Although typically much smaller than asteroid Eros, seen up close in this image from the NEAR-Shoemaker spacecraft, these objects pose a significant threat to Earth. The impact of an object much smaller than Eros would create a regional catastrophe far larger than any recently experienced on the planet. NASAUHUAPL

binary KBOs, whose evolution and dynamics are mysterious.

Information on the Kuiper Belt will help astronomers understand the origin and evolution of our solar system, while shedding light on planetary systems around other stars. But astronomers have barely scratched the surface. The LSST will carry out a census of the Kuiper population by discovering more than 10,000 KBOs. With such a large statistical sample, astronomers will have a grasp on one of the least-known regions of our solar system.

Studies of extrasolar planetary systems have yielded startling evidence that some giant planets have migrated — a process that may have happened in our solar system as well. The orbits of KBOs are the only fossil records of this activity. These orbits hold clues as to how bodies were shuffled around during the more raucous days of the early solar system. Because many KBOs (including Pluto) are in resonance orbits with Neptune, they can be used to measure how Neptune ejected mass from the solar system.

Dusty disks observed around other stars are no doubt replenished by collisions among Kuiper Belt-type objects. This seems common among young stars and may offer fundamental clues about the birth of planetary systems. Ironically, less is known about the disk of dust encircling our own solar system than those seen around other stars. And we know just as little about the small and dim objects orbiting beyond Neptune.

The LSST will be an invaluable tool for finding asteroids and comets zipping perilously close to Earth — collectively called Near-Earth Objects (NEOs). Astronomers estimate about 2,000 half-mile-wide (1-kilometer-wide) asteroids cross our orbit. But the LSST's wide and deep view, plus its observation frequency, will allow astronomers to catalog thousands of NEOs (including dim near-Earth comets) as small as a football field. Although not big enough to cause a global catastrophe, objects 500 feet (150 meters) across should not be overlooked. A small NEO could flatten a city with the energy equivalent of a 1,000-megaton explosion. Within ten years, the LSST could catalog 90 percent of asteroids with a diameter of 800 feet (250m) or bigger.

Sky patrol

The LSST will operate differently than most large telescopes. Rather than being used by individuals or groups carrying out more specialized observation programs, it will observe a preprogrammed series of fields, effectively imaging 10,000 degrees of sky every four nights.

The whole-sky images, built up over time to extremely faint levels, will provide critical support for follow-up research at a broad range of observatories. But the LSST's repeated imaging of each patch of sky means that science also can be done purely within the telescope's own database. Researchers, in other words, will not be dependent on follow-up observations from other telescopes.

All told, the LSST is expected to gather a mountain of data — 10 million gigabytes — and storing it in an accessible form will pose a huge technical challenge. The LSST archive will be the biggest database feeding into the Virtual Observatory, an ambitious plan to allow astronomers to tap into the major astronomical databases available today simultaneously.

No doubt, the LSST will be used for research projects undreamed of by its originators. Those efforts — which cannot be spelled out upfront or written into grant proposals — constitute a big part of the project's rationale.

"We are driven to build the LSST facility by what we know it can tell us about our universe," says Tyson. "But the biggest rewards may come from what we cannot predict."