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A Wide New Window on the Universe

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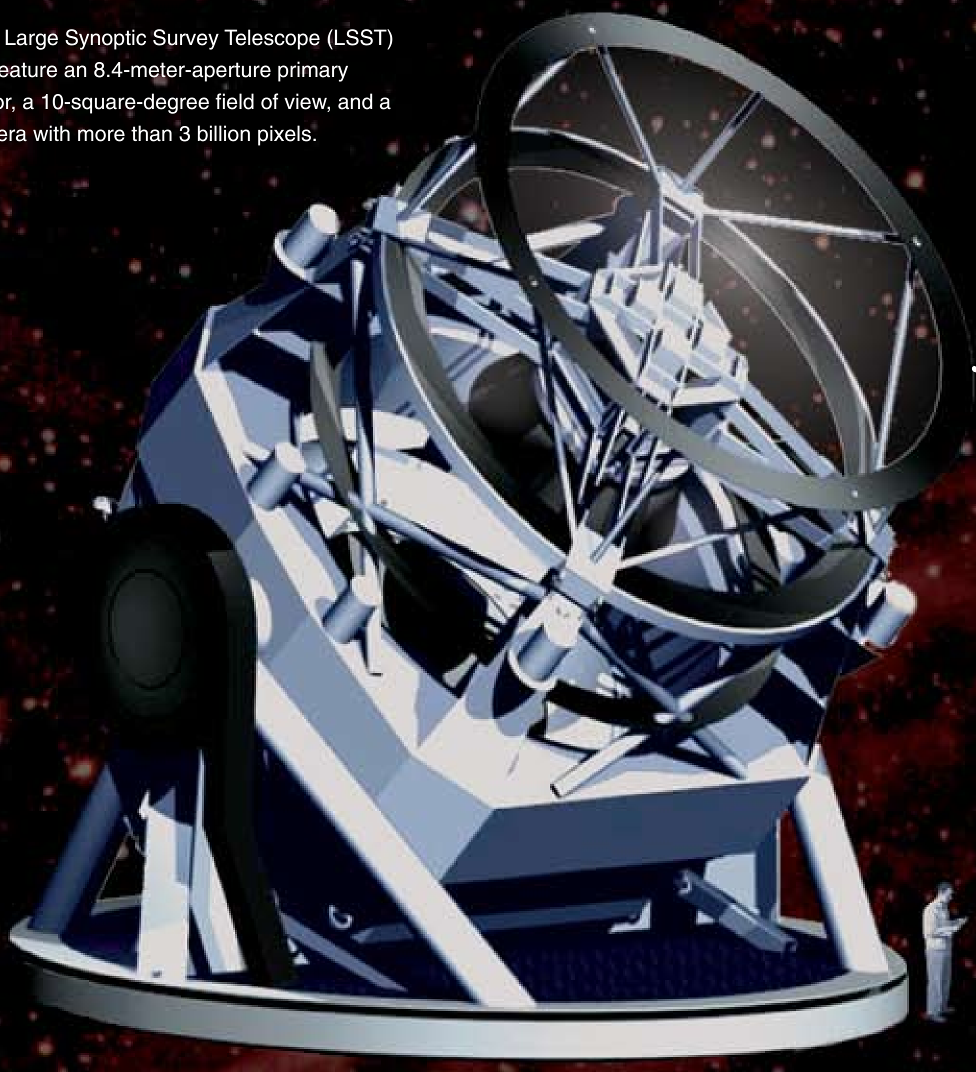
A Wide New Window on the Universe

By making frequent, detailed maps of the sky, the proposed Large Synoptic Survey Telescope will change astronomy forever.

The Large Synoptic Survey Telescope (LSST) will feature an 8.4-meter-aperture primary mirror, a 10-square-degree field of view, and a camera with more than 3 billion pixels.



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FOR decades, ground-based astronomy has consisted mostly of a lone astronomer earning the right to train a powerful telescope for a few nights on an extremely small patch of sky. If the astronomer is fortunate, a celestial discovery will be shared many months later with colleagues through a journal article or private correspondence.

Lawrence Livermore is a major partner in a new telescope project that promises to forever change that scenario—and all of astronomy—by taking advantage of advanced optical manufacturing techniques, digital imaging, supercomputer data processing, and the Internet. The ground-based Large Synoptic Survey Telescope (LSST), scheduled for completion in 2012, will provide, for the first time, digital imaging of objects, including changing events, in deep space across the entire sky. Data from LSST's astronomical surveys will be accessible almost immediately to astronomers and the public on the Internet.

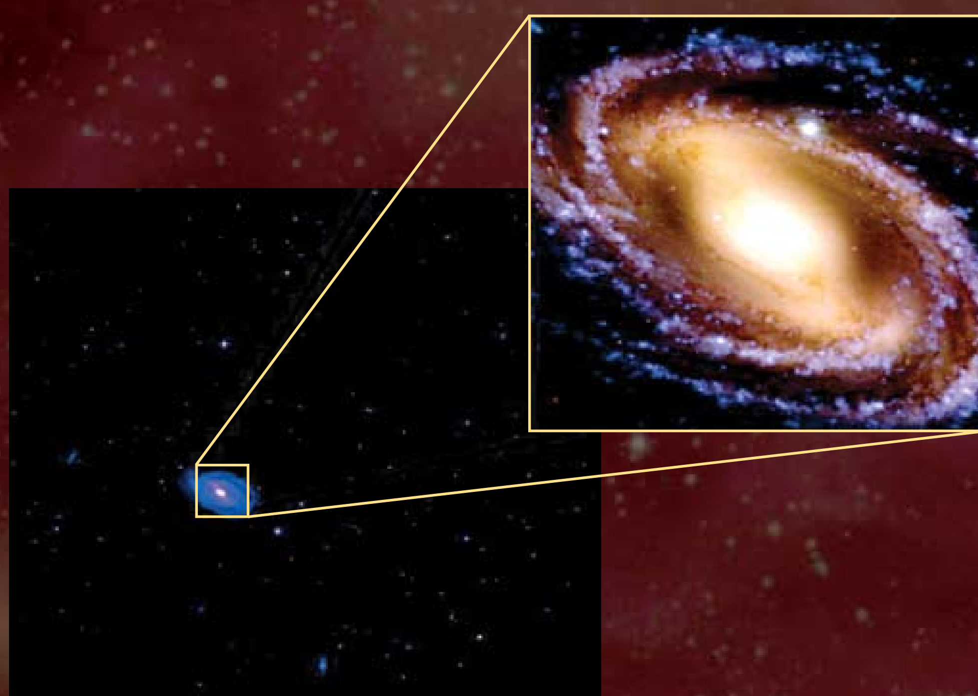
Over a span of three nights, LSST will construct a complete, detailed map of the sky using a telescope with a 8.4-meter primary mirror and an enormous detector. Of particular importance, the telescope will record objects that change or move, from exploding supernovae billions of light years away to comets passing close to Earth. The first complete survey produced by LSST may also provide clues about so-called dark matter and dark energy and new information about the nature and origin of the universe. Finally, LSST will catalog near-Earth objects to provide insight into the formation of the solar system and to warn Earth's inhabitants in the event of a potential collision with an asteroid.

Although a few telescopes with 8-meter-aperture mirrors exist, they are optimized to look deeply at small parts of the sky. Their small field of view makes it extremely unlikely that a single observation will catch a transient event. Furthermore, such an instrument would take many years to map the entire sky. Current all-sky maps made with smaller telescopes are limited in depth (faintness) and detail. LSST will overcome these drawbacks by mapping the entire sky deeply, rapidly, and continuously with a 10-square-degree field of view. What's more, when the telescope detects an object of interest, such as an exploding supernova, it will send out an alert for more specialized telescopes to follow up with higher resolution images.

Livermore researchers are participating in all aspects of the LSST project, from management to research efforts. For example, Bill Goldstein, associate director of the Physics and Advanced Technologies (PAT) Directorate, is on the governing board of the nonprofit LSST Corporation. Physicist Don Sweeney is the LSST project manager and manages the entire LSST effort from the project offices in Tucson, Arizona. Astrophysicist Kem Cook is a key member of the LSST science team and heads the Laboratory's LSST-related astrophysics research activities. Engineer Jim Brase is managing Livermore's participation.

Brase heads PAT's Optical Science and Technology Division, which develops advanced detectors for both astronomical research and national security. Most of the LSST research and development work is supported by Livermore's Laboratory Directed Research and Development (LDRD) Program, which is enabling scientists and engineers to develop new capabilities in optical instrumentation with both scientific and national security applications.

Brase says, "Astronomers traditionally apply for time on a remote telescope, but LSST will change everything." The telescope will be completely automated, building a huge database of celestial objects every night. Science will be done by astronomers doing "data mining," that is, finding unique features on LSST images they have downloaded from the Internet to their office computers. In this



The inset image is of the Spiral Galaxy M109 taken with the 6.5-meter Multiple Mirror Telescope in Arizona. The background image, from the Palomar Observatory Sky Survey, was taken in the 1950s with a 1.2-meter telescope using photographic plates. Each LSST exposure will cover the same area of the sky as the background image with the same high quality as the inset image.

way, scientists worldwide will have near-real-time access to astronomical developments that occur anywhere in the sky.

Livermore Is a Pioneer

Livermore helped pioneer wide-field, time-domain astronomy with the MACHO (Massively Compact Halo Object) project. Cook was a MACHO project founding member. Originally funded by LDRD, the project was a digital-imaging study in search of cosmic dark matter. (See *S&TR*, April 1996, pp. 6–11.) A key feature of the project was that astronomical events called gravitational microlensing were identified as they were happening, allowing detailed study by networks of telescopes. "The universe is an exciting place with major events occurring on time scales of minutes," says Cook. "We've missed almost all of these events in the past. LSST will do the first good job of watching the universe change on a large scale."

LSST will incorporate several technologies developed, for the most part, at Livermore. These include fabrication techniques for large optics developed for the recent generation of telescopes and the National Ignition Facility (NIF); detector technologies that allow cameras to capture wide-angle images on focal planes coated with billions of high-sensitivity pixels; and the technologies and tools for computing and storing large amounts of data.

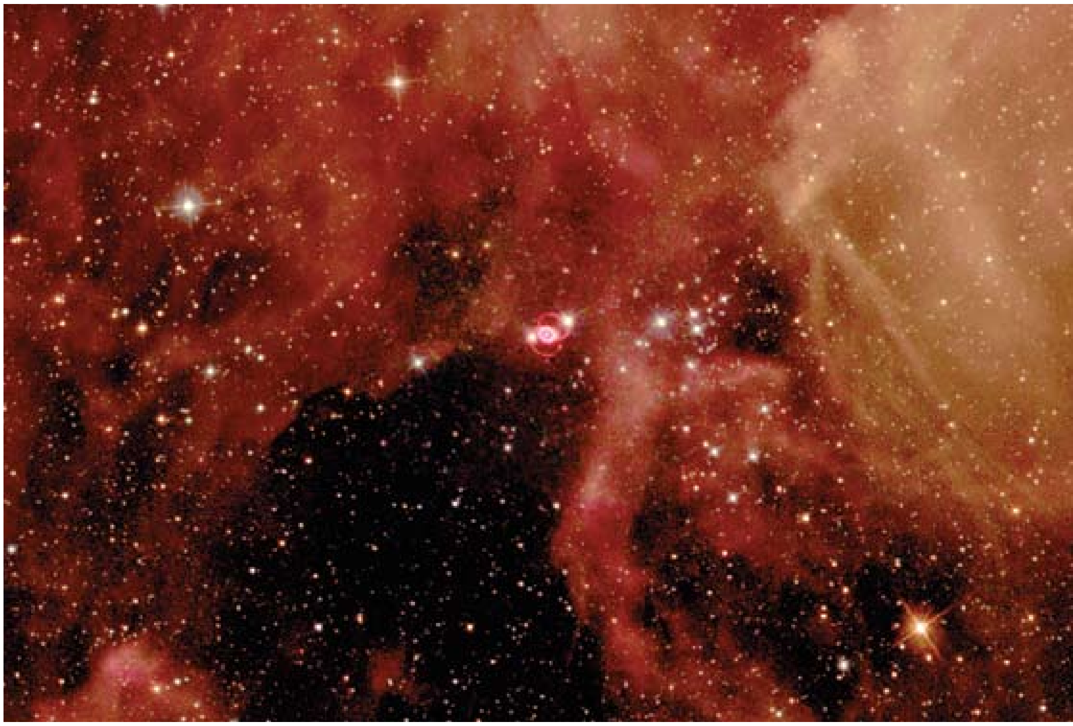
The telescope will benefit from Livermore's experience with optics, precision engineering, astrophysical research, and computing. NIF, currently being assembled at Livermore, will be the world's largest optical instrument. NIF scientists and engineers have worked with vendors to push the development of advanced optical components and coatings. Livermore scientists have also designed optics for land- and space-based telescopes and surveillance systems. Research in astrophysics is conducted at the Laboratory through its branch of the University of California's Institute for Geophysics and Planetary Physics. Livermore is also a world leader in supercomputing and in the managing, storing, and analyzing of enormous amounts of data.

The LSST project has been identified as a scientific priority in reports by several national panels. The effort to build the telescope is overseen by the nonprofit LSST Corporation, a collaboration of universities, national laboratories, and scientific organizations. The LSST team is considering three possible sites for the telescope: Las Campanas or Cerro Pachon in Chile and San Pedro Martir in Baja California, Mexico. The site will be selected in a year or so.

The estimated cost of LSST is about $300 million: $30 million for design and $270 million for construction. The funding will come from a partnership of private and federal sources. The LSST Corporation has already raised $25 million of private funding to jump-start the project and begin items such as the mirrors. The remainder is proposed to come from the National Science Foundation and the Department of Energy. The National Science Foundation recently announced that it will fund a 4-year, $14.2-million design and development project for LSST.

Optics Benefit from NIF

Livermore physicist Scot Olivier oversees the development of LSST camera optics, including lenses, filters, and mirror wavefront sensors as well as the mechanisms for keeping these components free of distortion. Olivier says, "We're leveraging our experience in



Astronomers predict LSST will detect more than 100,000 supernova explosions. This National Aeronautics and Space Administration (NASA) image shows Supernova 1987A in the Large Magellanic Cloud, a nearby galaxy. Astronomers witnessed the explosion of this star on February 23, 1987. The supernova remnant, surrounded by inner and outer rings of material, is set in a forest of diffuse gas clouds. (Photo courtesy of NASA.)

extreme ultraviolet lithography, precision engineering, adaptive optics, and NIF optics. The astronomical community has never built refractive optics for a camera this large or this powerful. We'll have the advantage of working with the same vendors who manufactured optics for NIF."

Layton Hale, a precision engineer, is devising the mechanisms that will hold optical components securely in place. The telescope's mount is being designed to ensure accurate tracking and repointing of the telescope quickly and repeatedly to adjacent locations.

Optical engineer Lynn Seppala designed LSST's mirrors and camera lenses. The optical-system design features three deeply curved mirror surfaces that collect light from objects as faint as 24th magnitude in a 10-second exposure, which is equivalent to the brightness of a golf ball at the distance from Earth to the Moon. Light gathered by the 8.4-meter primary mirror is reflected back up to the 3.4-meter convex secondary mirror and then down to the 5.2-meter tertiary mirror. Light is then bounced upward again through a series of three lenses to the camera detector suspended within the telescope structure. In a unique design choice, the primary and tertiary mirrors will be fabricated from a single piece of glass, 8.4 meters in diameter and more than a meter thick at the edge.

Wide Field of View

Three mirror surfaces allow high image quality over a wide field of view. The mirrors will provide a field of view encompassing 10 square degrees of sky, roughly 50 times the area of a full Moon. This field of view is more than 20 times that of existing large telescopes, yet LSST's light-gathering capability will be among the best in the world.

The tertiary mirror fits neatly into a hole of the primary mirror, offering the opportunity to construct a novel hybrid mirror. In January 2005, LSST Corporation awarded a contract to the University of Arizona's Steward Observatory Mirror Laboratory to begin fabrication of the hybrid primary and tertiary mirrors. Sweeney says, "Combining the primary and tertiary mirrors on a single 8.4-meter-diameter optical substrate is an engineering challenge never before undertaken."

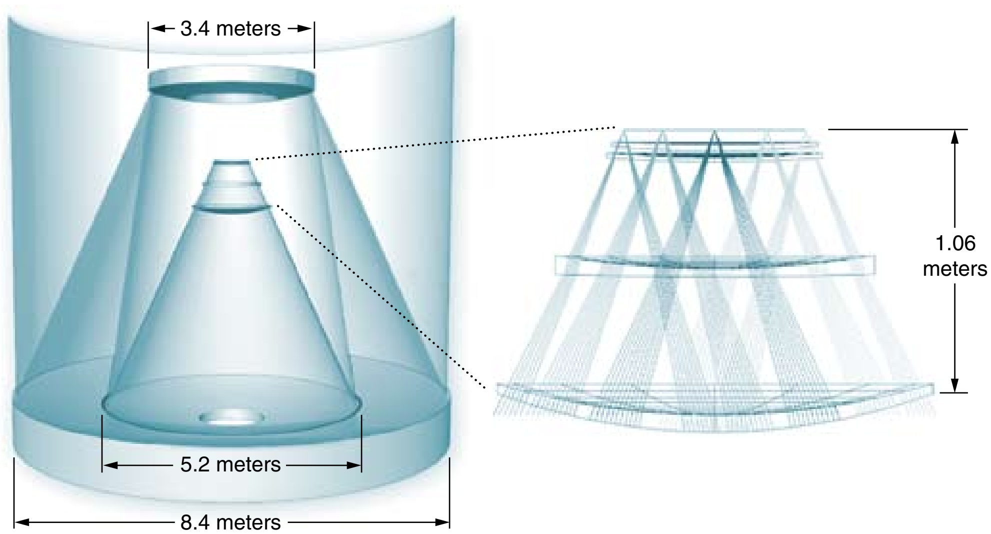
All LSST mirrors will be "active," that is, deformable by tiny actuators that ensure the mirrors maintain their proper shape. When the telescope points to a different area of the sky, or as temperature fluctuates during the night, the mirrors tend to bend, which would compromise their ability to focus a clear image.

Livermore researchers are designing a computer-controlled, wavefront-sensing system, in which the mirrors' shapes will be measured and adjusted by hundreds of actuators once every 60 seconds to within 10 nanometers of accuracy. The active optics and wavefront sensing system will also counter the turbulence in the atmosphere that degrades the quality of images from ground-based telescopes. According to Sweeney, "The completed LSST optical system will be the fastest, most compact system of this scale ever built for an advanced research telescope."

Livermore-built adaptive optics systems are used on large telescopes such as the University of California's (UC's) Lick Observatory on Mount Hamilton near San Jose and the Keck Telescope in Hawaii. In fact, nearly every large telescope in the world now has an existing or planned adaptive optics system.

Combining 1,000 Digital Cameras

To capture images produced over such a wide field, LSST will use a camera with three lenses, measuring 1.6, 1.0, and 0.7 meters in diameter. The camera will be combined with a charge-coupled device (CCD) and cover a 64-centimeter-diameter flat focal plane. The CCD will be the world's largest and contain more than 3 billion pixels. It is being designed as a circular mosaic of about 200 individual detectors, each comprising about 16 million pixels. Olivier says the combined detector will represent a huge extrapolation of consumer digital photography technology. "It's similar to combining 1,000 digital cameras, but unlike consumer digital cameras, this detector will be sensitive to more



Light gathered by the 8.4-meter primary mirror is reflected up to the 3.4-meter convex secondary mirror and then down to the 5.2-meter tertiary mirror. Light is then bounced upward again through a series of three lenses to the camera detector suspended within the telescope structure.

wavelengths." In particular, the detector will be sensitive to the near-infrared portion of the electromagnetic spectrum. It will thus detect light that has been "redshifted." (In an expanding universe the colors of stars moving away are shifted toward the red end of the spectrum.)

The camera will record images in five colors using 70-centimeter-diameter filters, the largest telescope filters ever manufactured. Five filters—green, red, blue, and two in the near-infrared region of the electromagnetic spectrum—will be inserted between both the second and third lenses. Sweeps of the sky in different colors will help provide information about the distance to each galaxy and the mass and evolutionary state of stars. Livermore engineers are leveraging NIF experience to design an automated system that will change the filters in 2 seconds or less.

The CCD-camera effort also involves participation by the Stanford Linear Accelerator Center (SLAC), Brookhaven National Laboratory, Harvard University, the University of Illinois, the National Optical Astronomy Observatory (NOAO), and UC Davis.

Negating Atmospheric Turbulence

Livermore physicists Leslie Rosenberg and Steven Asztalos, both researchers of

Scientific Missions

The Large Synoptic Survey Telescope (LSST) will compile a complete map of the entire sky, advance understanding of the nature and origin of the universe, and discover transient events. "No one knows what we'll discover," says Livermore physicist Jim Brase. For example, a new source brightening over a period of a few days with a particular color signature might be identified as one of several hundred thousand supernovae that LSST is expected to discover each year, located in galaxies billions of light years from the Milky Way. Other transient events include gamma-ray bursts and other unusual violent objects.

In one pass across the visible sky (14,000 square degrees, or about three nights of observation), LSST will detect and classify 840 million persistent objects. Astronomers worldwide will use the Internet to access the enormous—and ever-increasing—database of objects. A single 15-second exposure will detect sources at 24th magnitude with only a 10-percent error in magnitude. At this level of brightness, the most common objects in the sky are galaxies—60,000 of them per square degree across the sky.

Many parallel scientific missions can be conducted with this massive collection of data. For example, LSST will uncover new information about dark matter via weak gravitational lensing and supernovae studies. Dark matter (which dominates the mass of the universe) and dark energy are unseen phenomena whose existence has been inferred. A better understanding of these forces will help researchers determine how the universe is evolving.

LSST will help astronomers learn more about near-Earth objects such as comets and asteroids. These objects are composed of the material from which the solar system formed and thus hold important clues to the origin of the Sun and planets. Current efforts to find near-Earth objects are limited because asteroids and comets reflect little light, and telescopes do not have adequate light-gathering capacity or wide-area coverage. Astronomers estimate a one-in-10,000 chance exists that a 1- to 2-kilometer meteoroid will strike Earth within the century and cause enormous devastation. Therefore, asteroids represent a threat worth identifying and assessing.

LSST will also study the Kuiper Belt, the origin of most comets. The Kuiper Belt is a collection of minor planets orbiting beyond Neptune. It is the remnant of the disk of material that once orbited the Sun and produced the planets and their moons about 5 billion years ago.

NASA's Galileo Spacecraft took this image of the asteroid 951Gaspra. The asteroid measures 19 by 12 by 11 kilometers and is similar to those whose impacts could cause mass extinctions on Earth. It is one of thousands of near-Earth objects that will be imaged by LSST. (Image courtesy of NASA.)

dark matter, are analyzing the potential capability of LSST to provide images that would allow astronomers to learn more about the mysterious distribution of invisible dark matter and energy in the universe. "LSST will be taking images at incredible distances to the outer edges of the universe," says Rosenberg, who coordinates researchers from Livermore, UC Davis, SLAC, and NOAO.

To better understand dark matter, and to some extent dark energy, scientists depend on the phenomenon of gravitational lensing, the deflection of light by either visible matter or invisible dark matter. Astronomers study many images over several weeks to detect the subtle elongations caused by weak gravitational lensing. "We'll need to obtain incredible image quality from LSST because the changes caused by intervening dark matter are so small," says Rosenberg.

Unfortunately, atmospheric turbulence can mimic the elongation signal caused by gravitational lensing. Therefore, astronomers need to understand atmospheric turbulence so they can differentiate between elongations caused by the atmosphere and those caused by dark matter. In this respect, LSST's 15-second exposures pose a problem. At much shorter exposures, the irregular effects of atmospheric turbulence are frozen; however, at 15 seconds, they mostly average out. With LDRD funding, Rosenberg and Asztalos are completing a 3-year effort to evaluate the capability of LSST for detecting gravitational lensing in the presence of atmospheric turbulence.

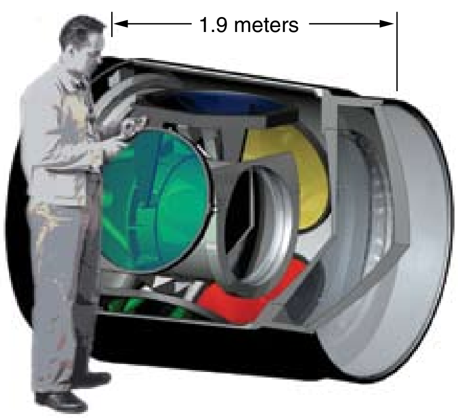
In May 2005, a team that included Livermore researchers traveled to Chile to acquire atmospheric data recorded from 4- and 8-meter telescopes as well as distant images of the universe taken by the telescopes. These data are the most comprehensive to date and have allowed Asztalos to simulate what an LSST image would look like by modifying a software program originally developed by astronomers at the California Institute of Technology. The program, which has been shared with other collaborators, models the sky, atmosphere, and LSST instrument. The simulations incorporate atmospheric-caused elongations.

"Our understanding of atmospheric effects based on results to date give us confidence that LSST can meet our goals to detect weak gravitational lensing," says Rosenberg. "However, we want to increase that confidence."

If LSST achieves the project's goals, it will be able to map out dark matter to enormous distances from Earth. In addition, by estimating distances to dark-mass concentrations, astronomers will be able to map dark energy. "Without a doubt, as soon as LSST sees first light, it will be the premier cosmology survey instrument," says Asztalos.

Data-Management Hurdle

Effectively managing the large amount of LSST data is the most challenging aspect of ensuring the project's overall scientific success, according to Brase. Livermore computer scientist Celeste Matarazzo is leading a data-management team that includes computational experts from Livermore, Johns Hopkins University, SLAC, and UC Davis and San Diego. The Livermore group, led by computer scientist Ghaleb Abdulla, takes advantage of extensive Laboratory experience in building large-scale computer and data-storage systems, performing data-intensive computing,



LSST's camera will record images in five colors using 70-centimeter-diameter filters. Five filters—green, red, blue, and two in the near-infrared region of the electromagnetic spectrum—will be inserted between the second and third lenses. This schematic shows the filters surrounding the third camera lens.

NASA's Hubble Space Telescope imaged the Abell 2218 massive cluster of galaxies located about 2 billion light years from Earth. The cluster is so massive that its gravitational field distorts light rays passing through it from faraway objects, as seen in the elliptical-shaped celestial objects. This phenomenon is called strong gravitational lensing. Weak grativational lensing is more subtle and must be measured by computer analysis.

maintaining large databases, and developing astronomical applications.

LSST will spend about 30 seconds observing a field of view before it is repointed to the next field. “The telescope must do sophisticated processing within that 30 seconds,” says Brase. For example, each image will be corrected for geometric distortions and ambient light from the night sky and mapped to a coordinate system. Any variations in sensitivity across the detectors will also be corrected. Stars and galaxies will be identified, and then the image will be added to data previously collected from the same location in the sky to build a very deep master image. All of these tasks will be done without human intervention.

Changes in an image will be revealed using image subtraction and a comparison against the database of known objects, allowing the type of change to be classified. If an object is moving or changing in brightness, the telescope will send out an alert to both ground- and space-based telescopes with the sky coordinates of the object of interest. One challenge is developing procedures for sending out automatic alerts. “We don’t want to send out false alerts,” says computer scientist Jim Garlick.

Abdulla notes that Livermore is building pipelines to efficiently process images by breaking the image up and processing each piece in parallel. Such a technique makes effective use of massively parallel supercomputers with thousands of microprocessors.

LSST will create 24 gigabytes of data every 30 seconds, a sustained data rate of 1,200 megabytes per second, unprecedented in astronomical data gathering. By comparison, the highest data rate in current astronomical surveys is about 4.3 megabytes per second. More than 30 terabytes of data must be processed and stored each night. One year’s worth of data from LSST will require the storage of more than 30 petabytes (10^{15} bytes). In comparison, the Hubble Space Telescope produces about 1 terabyte each year. Much of the science that will be done by astronomers will be accomplished with queries to this database. Garlick says that although the LSST data rate is challenging, “Big systems at Livermore move data around at comparable rates.”

Large computers will be located adjacent to the telescope. At least one supercomputer center in the U.S. will help process the huge amount of data. The chosen supercomputer will be similar to Livermore’s MCR or Thunder machines. Livermore computer scientist Don Dossa is chief architect of LSST’s computer system.

“We’ll be combining high-performance computing and databases in a new way,” says Abdulla. The Livermore team is anticipating how scientists will query the image database, especially when the same patch of sky will be imaged thousands of times.

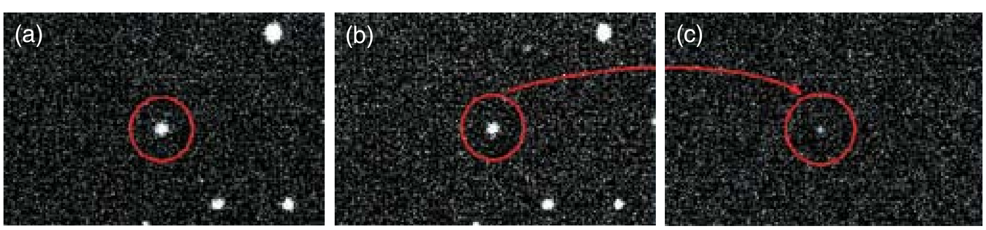
Excitement Building

As the work on LSST gains momentum, excitement in the astronomical community is building. By rapidly making complete digital sky maps, LSST will change astronomy forever.

Brase notes that image-probing techniques similar to those being developed for LSST are also important for other areas of science, such as satellite observations, biology, and oceanography. In addition, the software tools developed to mine the LSST data resource will find wide application. Livermore’s national security mission will benefit because LSST technologies have application to national and homeland security. For example, the LSST optical design serves as a prototype for future wide-field surveillance systems. Also, investments in astrophysics have enabled new capabilities for nuclear proliferation detection, such as lightweight nanolaminate optics, adaptive optics, multigigapixel camera systems, tools for image analyses, and data-search algorithms.

In just a few years, people worldwide will be turning to the Internet to find the latest digital maps of the universe.

—Arnie Heller



LSST will use image subtraction to discover supernovae. In this example, image (a) is subtracted from image (b) (taken three weeks later) to reveal that a supernova has exploded (c). Once LSST detects a supernovae, it will send out alerts to astronomers worldwide. (Photo courtesy of the ESSENCE project, National Optical Astronomy Observatory.)

Key Words: adaptive optics, asteroid, comet, dark energy, dark matter, gravitational lensing, Kuiper Belt, Large Synoptic Survey Telescope (LSST), National Ignition Facility (NIF), near-Earth objects, supernovae, wavefront sensing.

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