Multilayers Illuminate the Sun's Secrets

TELESCOPES from Earth and from space have imaged the sun millions of times but have discerned its secrets very slowly, especially those concerning its ever-changing magnetic fields. Now, extremely detailed images from a NASA satellite called the Transition Region and Corona Explorer (TRACE) are revealing the role played by fluctuating magnetic fields in heating the sun's hot plasma and creating such fantastic features as solar flares, eruptions, and loops. Obtained with a telescope using multilayer-coated mirrors produced by Lawrence Livermore scientists, the images can be assembled into mosaics of the complete solar body or arranged sequentially into astonishing time-lapse movies.

TRACE is part of NASA's Small Explorer program of lightweight spacecraft designed to minimize the cost of scientific space exploration. In Earth orbit since April 2, 1998, the 1,030-kilogram satellite continuously studies the key solar regions: the photosphere (the 6,000-kelvin surface), chromosphere (the part of the sun's atmosphere where the temperature rises to about 10,000 kelvins), transition region (between the chromosphere and corona in which the temperature rises dramatically to 100,000 kelvins), and the corona (the multimillion-kelvin upper atmosphere).

TRACE observes the sun at unprecedented spatial resolution (1 arc second, or 740 kilometers across) and time resolution (from 2 to 30 seconds between images). Images at these resolutions effectively provide time-lapse movies that reveal how extremely fine magnetic loops appear, evolve, and reform.

Key to the high image resolution are the multilayer optical coatings produced by a Lawrence Livermore team led by materials scientist Troy Barbee, Jr. Multilayers are composed of alternating layers of two different materials as thin as a few atoms. (See "Atomic Engineering with Multilayers," *S&TR*, December 1997, pp. 12–19.)

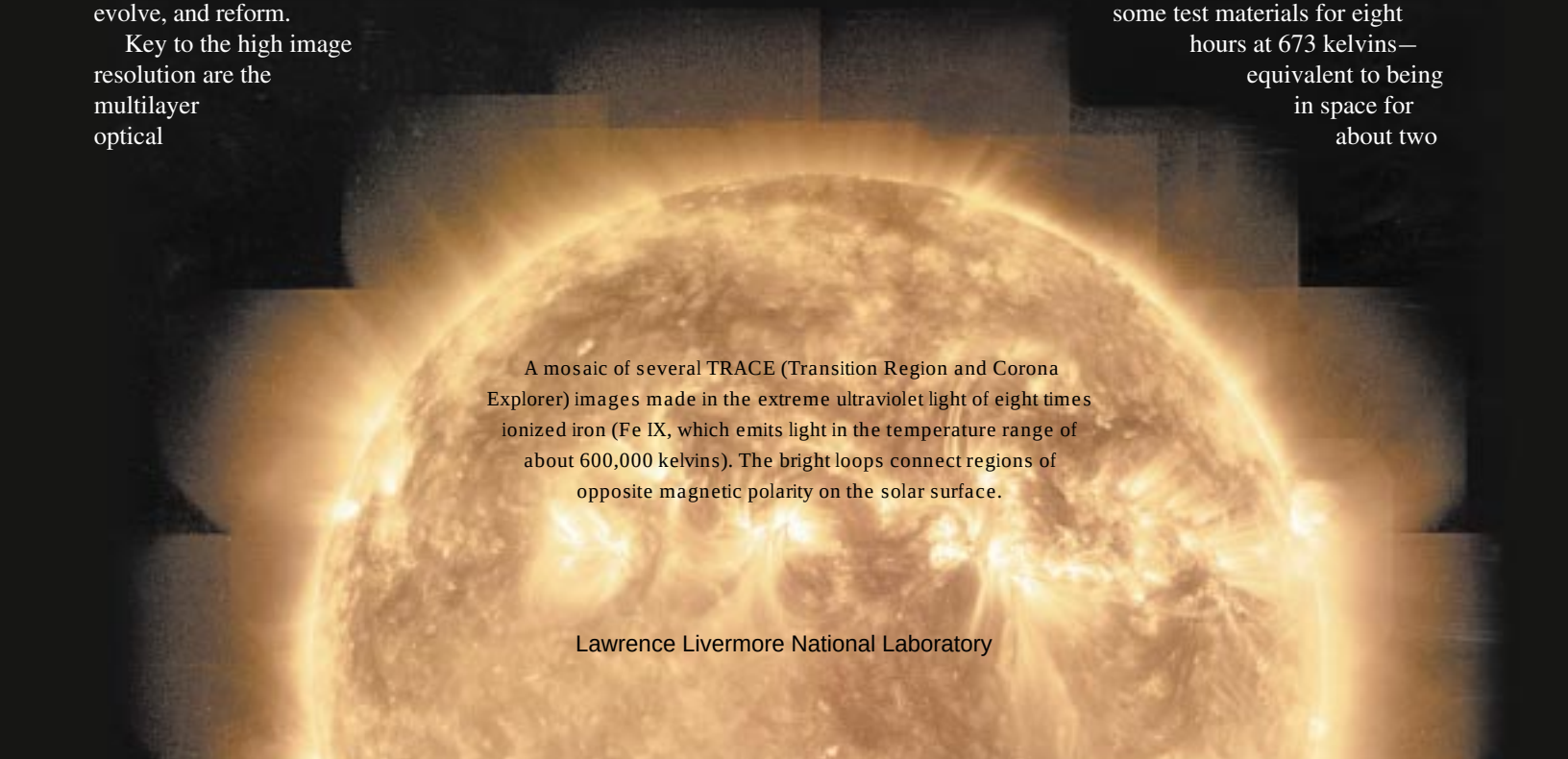
In recent years, multilayers have proved extremely valuable to astrophysicists for their ability to focus light in previously inaccessible narrow bands of the x-ray, soft x-ray, and extreme ultraviolet wavelengths. Their extraordinarily efficient optical performance reveals astronomical features that cannot be captured by instruments operating at longer wavelengths.

Wanted: Higher Resolution

When planning for the mission began, says Barbee, the TRACE team asked for multilayers that could provide much higher resolution and reflectivity than had ever been achieved. The team also requested more robust materials; previous space-born multilayers have degraded in time as a result of the harsh environment.

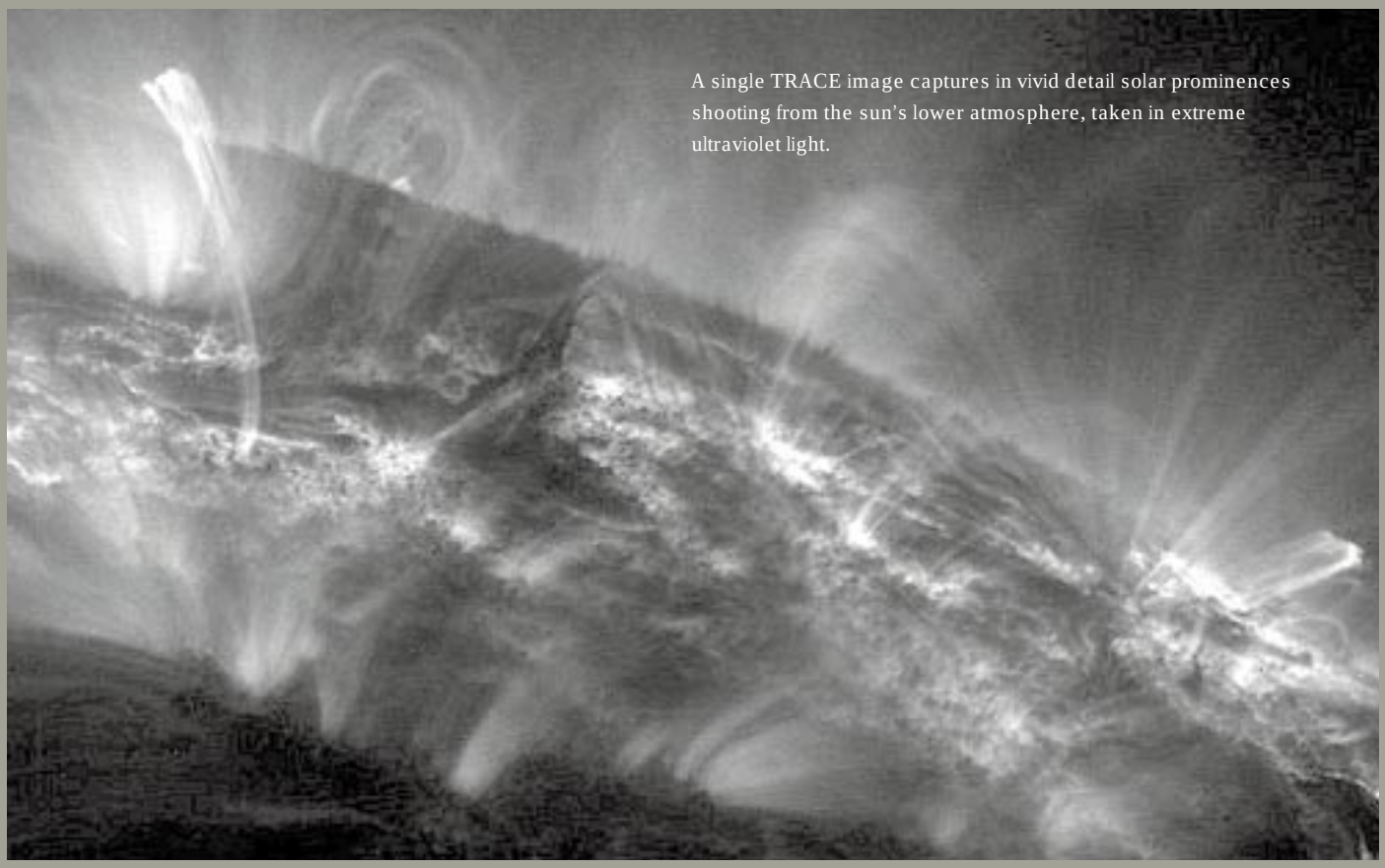
In response, Barbee's team developed multilayers made of alternating layers of molybdenum carbide and silicon. The multilayers were applied to a substrate of titanium silicate glass, supplied by the group at the Smithsonian Astrophysical Observatory responsible for TRACE optics.

Barbee reasoned that the carbon in the molybdenum carbide reacts with silicon to form silicon carbide, an extremely stable material, at the interfaces between the layers. To test the multilayers' stability, Barbee annealed some test materials for eight hours at 673 kelvins—equivalent to being in space for about two



A mosaic of several TRACE (Transition Region and Corona Explorer) images made in the extreme ultraviolet light of eight times ionized iron (Fe IX, which emits light in the temperature range of about 600,000 kelvins). The bright loops connect regions of opposite magnetic polarity on the solar surface.

Lawrence Livermore National Laboratory



A single TRACE image captures in vivid detail solar prominences shooting from the sun's lower atmosphere, taken in extreme ultraviolet light.

years at 90°C. No changes were observed in the performance of the annealed structures, demonstrating that they are dramatically more stable than other potential multilayer material combinations. In space, the TRACE multilayers have proved so stable that they are used to calibrate multilayers on other satellites.

The Livermore materials are exceptionally smooth and flat; their 47-percent reflectivity is a factor of 2 better than any multilayer previously used in space. Such high reflectivity results in much shorter exposure times for the satellite's charge-coupled device (CCD) camera.

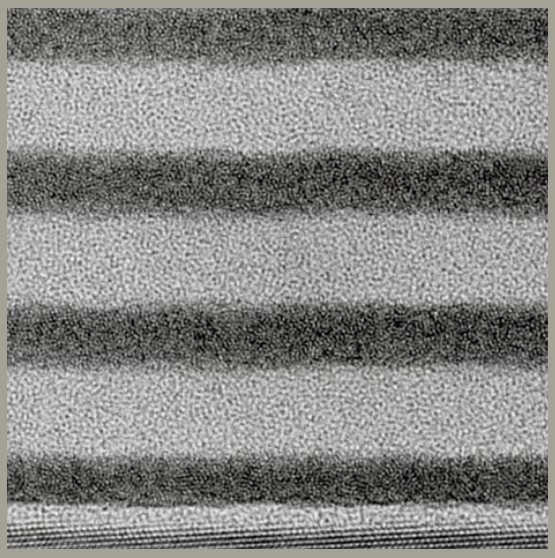
The 30-centimeter primary TRACE telescope has a different multilayer coating on each quadrant of its surface, making it in effect four different telescopes. The telescope shutter selects one quadrant at a time. Coatings for three quadrants were each designed for a specific band of extreme ultraviolet light corresponding to one of these excited ions of iron: Fe IX, Fe XII, or Fe XV. These three excited states are formed at temperatures of 600 thousand, 1.5 million, and 2 million kelvins, respectively.

The fourth quadrant of the telescope reflects visible and ultraviolet light; a filter wheel near the focal plane selects this light from the regions of 6,000 to 30,000 kelvins. One piece of the surprising information yielded by TRACE's high-resolution images is that temperatures in the outer solar atmosphere vary from less than 30,000 to more than 2,000,000 kelvins over distances of only a few thousand kilometers.

Putting Observations Together

By combining observations taken at different wavelengths only a few seconds apart, scientists can follow the evolution of the sun's magnetic fields from the photosphere into the highest reaches of the corona. The quality of the images is further refined by internal stabilization of the telescope optics against spacecraft jitter.

To date, more than two million TRACE images have been captured and relayed to Earth for analysis. Viewed individually, combined into giant mosaics, or rapidly sequenced as time-lapse movies, the images have sparked a revolution in understanding solar atmosphere dynamics, especially those events occurring in the transition region and corona. "We're seeing for the first time how magnetic fields determine solar phenomena," says TRACE principal investigator Alan Title, solar astrophysicist at the Lockheed–Martin Solar and Astrophysics Laboratory and physics professor at Stanford University.



TRACE multilayers are made of extremely thin, alternating layers of molybdenum carbide and silicon, as seen in this electron micrograph at about 4 million times magnification.

Title says that aside from observations from a couple of five-minute rocket flights into the Earth's atmosphere, the sun's corona had not been seen with such resolution. "Suddenly, TRACE extended our observing window from five minutes to several years."

TRACE observations, he says, reveal a richly detailed portrait of the corona, where magnetic fields play a dominant role. Especially obvious are bright loops of different lengths of plasma that connect regions of opposite magnetic polarity.

"The images show that virtually all of the sun's loops have a structure at scales near or below the CCD camera's resolution of 1 arc second," says Title. "No one had appreciated that the solar atmosphere was as finely detailed and as rapidly evolving as we're seeing with the TRACE movies. We really hadn't expected so much information."

Title cites the light-gathering capabilities of the multilayer mirrors, which permit taking rapid sequences of images. "If you're only taking a picture every 15 minutes, magnetic waves with periods of a few minutes don't get recorded."

Important Data with Multiple Uses

The data are important to NASA and other agencies because magnetically induced solar events, such as flares and coronal mass ejections, can have huge consequences millions of miles away. Although they last only a couple of minutes, large flares emit enormous amounts of high-energy radiation and fast particles that can endanger astronauts, disrupt satellites in orbit, and even cause power outages in electrical grids on Earth.

The problem of flare emission and coronal mass ejection is sufficiently important that a National Sun Weather Program has been established. A better understanding of the physical processes in the outer solar atmosphere is also important to astronomers for understanding the processes of other stars and to magnetic fusion scientists for designing methods to confine hot plasmas and produce magnetic fusion energy.

The wealth of information contained in images from TRACE and other solar satellites was the focus of an international conference held at Monterey, California, in August 1999 that was attended by scientists from the U.S., Japan, China, Europe, Russia, and Canada. Barbee, who attended the conference, says the proceedings showed that TRACE observations are forcing a reconsideration of traditional theories underlying the physics of the sun and its atmosphere.

In particular, he says, TRACE movies are providing new insights into how the corona becomes heated to extremely high temperatures by magnetic fields. Astrophysicists have long been perplexed by the fact that the sun's outer atmosphere is so much hotter than its surface; computer models have not accounted for this heating satisfactorily.

Images and movies are not reserved for scientific investigators. TRACE is the first U.S. research mission with a completely open policy; all data are available to other scientists, students, and the general public soon after they become available to investigators. Sample movies of TRACE images can even be seen on the Internet at http://vestige.lmsal.com/TRACE/.

Barbee points out a final and seemingly unrelated payoff to the successful application of multilayers in solar astrophysics: computer chip manufacturing. Multilayer mirror coatings are a key technology for extreme ultraviolet lithography (EUVL), now under development by Lawrence Livermore and its industrial research partners. The technology promises manyfold increases in computer performance by shrinking the size of lines and features within chips. "The first images of the sun with multilayers in 1987 really put EUVL in motion," says Barbee. "We demonstrated we could get these resolutions, so the researchers pushed ahead in the lithography area."

From the vast atmosphere of the sun to the tiniest computer chips, multilayers are helping scientists push ahead on many fronts.

—Arnie Heller

Key Words: chromosphere, corona, extreme ultraviolet lithography (EUVL), multilayers, photosphere, sun, Transition Region and Corona Explorer (TRACE).

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Of Mice and Men

RODENTS and people may not appear to be closely related, but consider this the next time you look in a mirror: the genes of human beings and mice are 85 percent identical. This similarity is one of the reasons Lawrence Livermore scientists are studying mice. At Livermore's Human Genome Center, biomedical scientist Lisa Stubbs is leading a team that is studying the mouse genome to better understand the functions of human genes. Comparative genomics—analyzing and comparing the genetic material of different species—is viewed by bioscientists as an important method for studying evolution, the functions of genes (what they do and why), and inherited diseases.

Hunting Down Damaged Chromosomes

The mice used by Stubbs and her team were initially bred at the experimental mouse genetics facility at the Oak Ridge National Laboratory, one of the largest of such facilities in the world. It was originally established to conduct genetic risk assessment and toxicology studies. The mice brought to Livermore comprised some 130 unstudied mouse family lines, descendants of mice that were exposed years ago to radiation or chemicals for the purpose of studying the genetic effects of these agents. The offspring of the original mice were normal, although they were carriers of a mutation. But some of the descendants of those offspring, inheriting two copies of a mutated gene, showed anomalies (phenotypes) that are visible signs of the genetic mutations. Stubbs brought the carrier mice to Livermore in 1997 to identify inherited traits associated with the mouse lines and to find the genes disturbed by each mutation. "We look for phenotypes such as deafness, movement disorders, limb deformities, obesity, and susceptibilities to cancer," says Stubbs. If the trait is passed down to successive generations of a single mouse line, the team knows it is genetic.

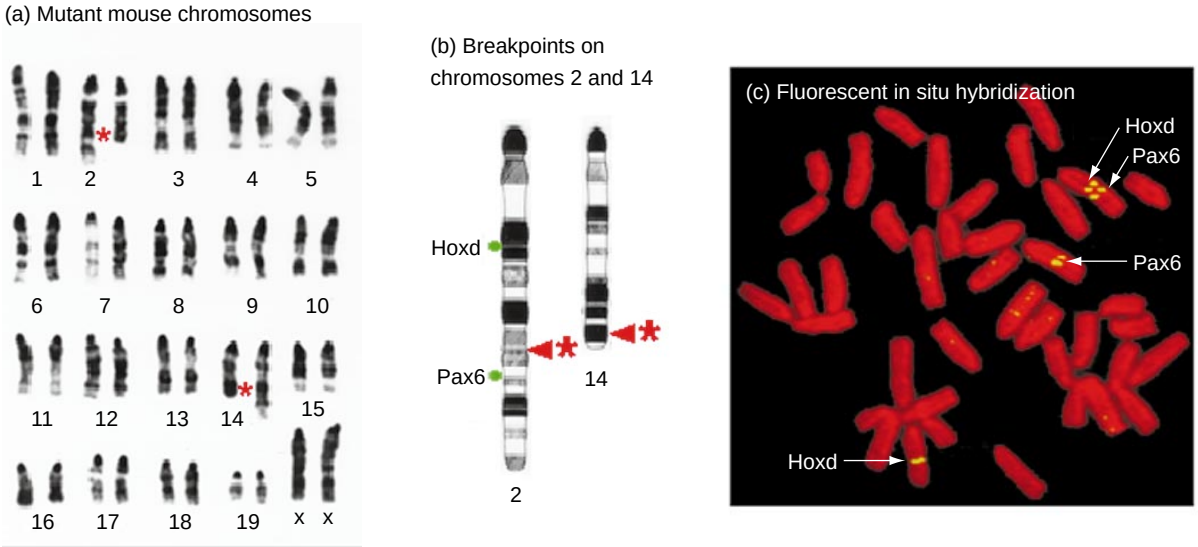
To find out which gene is responsible, a researcher takes a small snip of skin from a mouse tail and grows the skin cells in a petri dish. Chromosomes from those cells are then spread on a microscope slide. In the laboratory, the researchers look for one particular kind of mutation called a translocation, which involves obvious changes in chromosome structure. Because the chromosomes are visibly disrupted, researchers can easily map the position of the mutated gene using only a simple light microscope. For example, the figure at right shows two mouse chromosomes—2 and 14—where such a translocation has occurred. "We knew immediately that the gene responsible for the trait would be found on one of those two chromosomes," Stubbs explains.

The researchers then use a procedure called fluorescent in situ hybridization (FISH), a technique for painting chromosomes with a fluorescent dye, to pinpoint the gene's location. They label a gene from a normal chromosome 2 with the fluorescent dye and add it to a slide containing the mutant mouse chromosomes. The labeled gene probe recognizes DNA sequences spread over the slide that are identical to its own and binds to the chromosome at that site. "In this way," Stubbs says, "we can map any gene relative to the translocation and 'trap' the mutated gene in a small, well-defined region."

The researchers repeat the process for other genes on chromosome 2 until they have narrowed down the "breakpoints," that is, the end pieces of the two broken and rejoined chromosome segments. Once they zero in on the chromosome section involved, they search the

Laura Chittenden, Lawrence Livermore biomedical scientist, with furry friend. This rotund mouse has a chromosomal defect in an unknown gene that leads to obesity.

Lawrence Livermore National Laboratory



Translocations are a type of mutation that change chromosome structure and can be detected by looking at stained chromosomes under a light microscope. In (a), a translocation involving mouse chromosomes 2 and 14—caused by breaking and rejoining of those two chromosomes—is shown. The mouse carrying these translocations has one normal (at left) and one mutant (at right) copy of each chromosome. (b) The locations of the chromosome breaks, marked by arrows, are determined by comparing the light- and dark-staining bands of normal vs mutant chromosomes. The break marks the location of the gene that no longer functions correctly. (c) To map the mutant gene more precisely, researchers paint genes from a normal chromosome (in this case, the genes Hoxd and Pax6 on chromosome 2) with fluorescent dyes and mix them with chromosomes spread over a microscopic slide. Here, both painted gene "probes" bind to a normal chromosome 2 that contains an identical sequence of them. But two other chromosomes show only one binding gene probe each, because the translocation has occurred in the region between the two genes and has separated them. The translocation maps the mutated gene to the region between Hoxd and Pax6 on chromosome 2.

Of Human Genes and the Department of Energy

Humans have 23 pairs of chromosomes that are made up of DNA (deoxyribonucleic acid), chemical characters arrayed in a particular order in a chain. The chromosomes contain the three billion characters that make up the human genome.

Sequencing is the work of determining the exact order of four individual chemical building blocks that form DNA. These four chemical bases—commonly abbreviated as A, G, C, and T—bind together to create base pairs of DNA molecules. After researchers sequence a piece of DNA, they search for the special strings of sequences that form genes.

The Department of Energy's Joint Genome Institute (JGI) combines the work of Lawrence Livermore, Lawrence Berkeley, and Los Alamos national laboratories. JGI operates around the clock as researchers work to determine the sequence of the information-carrying units that comprise the DNA of three human chromosomes—5, 16, and 19—as part of the international effort to decipher the human genetic code. The purpose is to understand the genetic basis of life. This understanding, in turn, will enable us to understand and attack the root causes of hereditary disorders and susceptibility to diseases such as cancer, heart disease, stroke, diabetes, schizophrenia, Alzheimer's disease, and many others. Because comparison to genomes of other, distant species such as the mouse aids in the discovery and analysis of genes embedded in the human sequence, the JGI will also contribute significantly to sequencing of the mouse genome. That sequencing is part of an international effort slated to proceed in earnest as the human sequence nears completion.

DNA sequence of that region to identify the genes that have been disrupted by the chromosome break.

"By the time we go to the DNA sequence and begin searching out individual genes," Stubbs says, "we know exactly which spot on the chromosome we must deal with." She continues, "When an organism is exposed to radiation or chemicals, we don't know ahead of time which genes will be affected. It's random, like potluck. All genes 'do something,' but some genes are less important than others—their activities affect our development or our health in very subtle ways. If such genes are mutated, we see no visible effects. Others genes, such as those that predispose someone to cancer or obesity, are essential, and their mutations have very obvious impact. All of our mice have mutations. But by focusing specifically on those

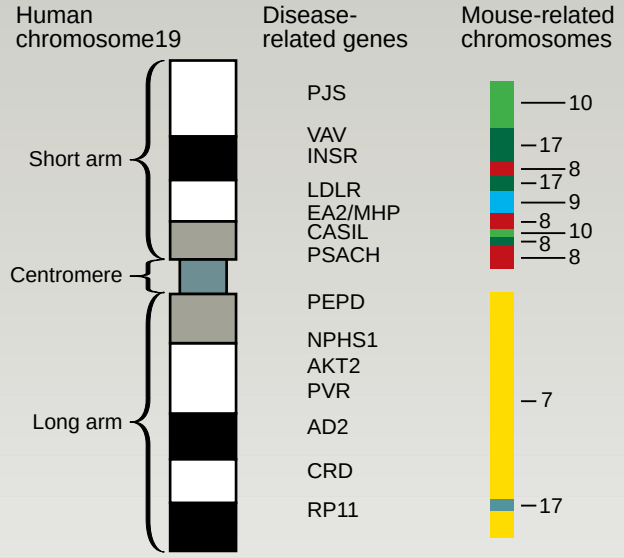
Similar but Different

Imagine taking human chromosomes, shattering them into pieces of varying lengths, and putting them back together in a different order. "That's what mouse chromosomes look like," says Lisa Stubbs, a Lawrence Livermore bioresearcher. For instance, as the figure shows, almost all of the long arm of human chromosome 19 is related to mouse chromosome 7. That is, the two chromosomal regions contain human and mouse versions of the same genes, organized roughly in the same order. In contrast, the short arm of human chromosome 19 comprises nine segments, each containing 20 to 100 genes and corresponding to different mouse chromosomes. Despite this scrambling of the genetic material, gene content and order within each mouse and human segment mirrors the other quite closely. Humans have this genetic material contained in 23 pairs of chromosomes, whereas mice have 20 pairs. But this difference reflects organization of genes and not their relative numbers.

Humans and mice also have about the same number of genes—now estimated to be approximately 140,000—and with some exceptions, each human gene has a clear and quite similar counterpart in the mouse. Those rare exceptions may prove to be quite important to the differences between humans and mice and must be understood more fully. For example, mice have some members of the cytochrome gene family that encode proteins needed to metabolize toxins, which humans do not possess. This genetic difference is reflected in the fact that mice and humans deal with certain toxins differently. Likewise, humans carry a gene encoding a protein called Apo(a) that plays an important role in developing atherosclerosis. Normal mice do not have the gene and never exhibit the symptoms of this deadly cardiovascular disease.

However, these species-specific genes altogether account for roughly 1 percent or less of the two gene sets and do not determine all the differences between humans and mice. The major differences between the species arise from the wide variation in the coding sequences of the counterpart genes. When the average 15 percent difference in mouse and human protein coding sequences is multiplied by 140,000 genes, the overall genetic difference is quite significant.

Not all genes are indispensable, and many of the differences found when mouse and human genes are compared have little effect on our biology. Many living organisms, including humans, carry single-gene changes and chromosomal defects such as translocations (swapped bits) and deletions (missing bits). These changes can mean nothing, or everything. "Consider," says Stubbs, "that because of the large coding capacity and complexity of the genome, a mere 15 percent difference in genes gives you a completely different organism—a human instead of a mouse. But turning the tables around, it is also quite remarkable that humans and mice are as genetically similar as we actually are."



That the human and mouse genomes are both similar and different is shown here. The long arm of human chromosome 19 has a close counterpart in mouse chromosome 7—the human and mouse versions of the same genes (see middle column) are found in them in roughly the same order. However, genes in human chromosome 19's short arm correspond to mouse versions that are located in many different mouse chromosomes, as indicated by colored bars to the right, labeled by chromosome number.

with visible abnormalities, we are aiming at those genes that play the most important roles in maintaining health."

Tracking a Cancer Gene

One case the team researched involves a particular kind of stomach cancer known as adenocarcinoma. In some cases, this cancer begins with the *Helicobacter pylori* bacteria commonly found in human stomachs. Although many people carry these bacteria, only some develop chronic gastritis—a painful inflammation of the stomach lining. If the bacterial infection is left untreated, many of the infected will develop a low-grade stomach lymphoma, which can progress with time. A small but significant percentage of lymphoma patients will eventually develop adenocarcinoma if the bacterial infection persists long enough. "We know," says Stubbs, "that whether or not one develops gastritis and cancer is determined at least in part by genetic predisposition. However, no one knows which genes encode these predisposing factors."

The stomach cancer issue arose when Stubbs identified a family of mice susceptible to gastritis, lymphoma, and adenocarcinoma. "This mouse mutant family develops a disease that looks precisely like what has been documented in susceptible, *Helicobacter*-infected people," says Stubbs. "These mice therefore provide a unique model for tracing the elusive genetic susceptibility factors."

The first thing the researchers did was to raise this mouse family in an environment without *Helicobacter* or other known pathogenic bacteria. "Although mice that have been exposed to bacteria quickly develop lymphoma," she says, "these pathogen-free animals did not. However, they did exhibit precancerous changes in cells of the stomach lining. We are observing some of those animals over time to see if the precancerous changes will progress to adenocarcinoma. Our hypothesis is that the genetic defect carried by these mice makes them susceptible to infection. But because they develop precancerous lesions without bacteria, the mutation must also mimic the effects of bacterial infection in some unknown but important way."

Using the FISH technique, they tracked down a mutation in a gene that produces a component of the mucus normally coating the intestinal lining. The mutant mice turn this gene on in the wrong location—the stomach—and have the properties of their stomach linings altered in significant ways. "It may be," says Stubbs, "that people who have a defect in the corresponding human gene may also have a higher susceptibility to this kind of stomach cancer. We hope to verify this possibility in future research."

For the Future: Playing Off the Strengths

On the one hand, much less sequencing has been completed for the mouse than for the human genome. On the other hand, a wealth of knowledge exists regarding the inheritance of genetic traits in mice.

Every family has some undesirable hereditary trait—whether near-sightedness, obesity, asthma, allergies, high cholesterol, or other ailments. In such cases, says Stubbs, it's almost impossible to see the pertinent genetic signal over the general noise of random—and often unimportant—changes that distinguish our highly varied genomes. Humans are a heterogeneous population with a huge amount of genetic variation—some important, some not. Which change is the one that accounts for the asthma, the obesity? "Mutant mice will help us find out," says Stubbs. "We can study groups of mice that are genetically identical, like identical twins, except that one mouse carries a mutation in a single, unknown gene. Because the background is stable, we can follow the activities of that single gene with good certainty. We study the pathology of the mutant mouse, track down the gene involved, and then identify its human counterpart to study whether that gene plays a role in human diseases with similar pathology [see box on p. 16 for comparison of mouse and human genes]. Knowing which gene is responsible for a health disorder is the first step toward designing treatments to alleviate the condition."

The mouse is a powerful genetic model that is being used worldwide for gene-function studies. As new information about human genes is developed at the Department of Energy's Joint Genome Institute and through the international sequencing effort, there will be more and more new genes to study and understand. And as more and more health-related genes—such as those for obesity, deafness, and developmental disorders—are discovered first in the mouse, the power of studying a human gene through its mouse counterpart is increasingly obvious. Stubbs sums it up this way: "It's very exciting to be working at the center of the next wave of genome research."

—Ann Parker

Key Words: adenocarcinoma, chromosome, comparative genetics, DNA, fluorescent in situ hybridization (FISH), gene, Human Genome Center, Joint Genome Institute, translocation.

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For more genetic research information, see these Web sites:
http://wwwbio.llnl.gov/genome/genome.html.
http://www.jgi.doe.gov/JGI_about.html.
http://www.ornl.gov/TechResources/Human_Genome/publicat/primer/intro.html.

Experiment Mimics Nature's Way with Plasmas

FOR the past decade, most research in magnetic fusion energy has centered on the doughnut-shaped tokamak approach to generating fusion reactions. Tokamak work continues in the United States and abroad, but Department of Energy fusion energy scientists are also revisiting the spheromak, an alternative concept for attaining magnetic fusion.

Much of the renewed interest in spheromaks is focused on a research effort at Lawrence Livermore called the Sustained Spheromak Physics Experiment (SSPX). The SSPX was dedicated on January 14, 1999, in a ceremony attended by representatives from DOE and collaborating scientists from the Sandia and Los Alamos national laboratories. SSPX is a series of experiments designed to better determine the spheromak's potential to efficiently contain hot plasmas of fusion fuel, in this case, the hydrogen isotope deuterium.

According to SSPX leader David Hill, the tokamak concept is considered the leading contender to generate sustained fusion reactions by heating plasmas to more than 100 million degrees Celsius (much hotter than the core of the sun) and confining them with magnetic fields. However, the tokamak's magnetic fields are generated by large, external magnetic coils surrounding the doughnut-shaped reactor. These large coils would increase the cost and complexity of generating electricity.

Spheromaks, however, confine hot plasma in a simple and compact magnetic field system that uses only a small set of external stabilizing coils. The necessary strong magnetic fields are generated inside the plasma by what's known as a magnetic dynamo. In this regime, the plasma—fast-moving, superhot ions and electrons—produces its own confining magnetic fields. The magnetic fields pass through the flowing plasma and generate more plasma current, which in turn reinforces the magnetic fields.

The powerful internal currents and magnetic fields become aligned so that they are nearly parallel to each other. Together, they form what Hill describes as something akin to a very hot smoke ring made of electrical currents.

Simple Design, Complex Behavior

"The beauty of a spheromak is that the main magnetic fields are generated by the plasma itself. It's a physical state the plasma wants to make naturally," Hill says. Indeed, the spheromak state is produced by the same mechanisms responsible for the behavior of galactic jets, solar prominences, and Earth's molten magnetic core.

Many scientists believe the spheromak's simple design and lower operating costs make it a potentially better candidate than the tokamak for a power-producing fusion reactor. "Tokamaks are big and expensive," says Hill. "If one coil goes down, it's a big repair job."

Technician Richard Kemptner adjusts the high-voltage lines that initiate the plasma in the 1-meter-diameter vacuum vessel.

Lawrence Livermore National Laboratory

Although the physical spheromak design is simple, its dynamo activity produces plasma behavior that is extremely complex and more difficult to predict and control than that found in tokamaks. Livermore researchers are guided in understanding this plasma behavior by accumulated theoretical expertise and by CORSICA, an advanced Livermore simulation code developed over the past decade. (See *S&TR*, May 1998, pp. 20–22.)

The SSPX is the latest of the experiments in magnetic fusion energy research that date back to Lawrence Livermore's founding in 1952. Over the years, Lawrence Livermore scientists performed some of the pioneering spheromak work, along with Los Alamos National Laboratory and other DOE and university research centers.

Enthusiasm for spheromaks waned in the early 1980s, however, when experiments at Los Alamos and other facilities achieved lower temperatures than experiments using tokamak designs. As a result, the nation's magnetic fusion research community focused on advancing the tokamak design, while spheromak research continued in Japan and Great Britain.

Reanalysis Revived the Concept

Interest in reviving the spheromak concept was triggered by a review of data from key Los Alamos experiments conducted more than 10 years ago. A thorough reanalysis led by Ken Fowler and Bick Hooper, former associate director and the assistant associate director, respectively, for Magnetic Fusion Energy at Livermore suggested that the plasma's energy confinement was up to 10 times better than originally calculated.

The analysis also showed that plasma confinement improved as the temperature increased. The thinking, says Hill, is that as temperatures increase in the spheromak, electrical resistance in the plasma decreases, so fusion reactions can occur more easily.

In light of the reanalysis, the scientific community and DOE managers considered it worthwhile to pick up where the Los Alamos experiments left off some 10 years earlier. Hill notes that the experiment is one of several alternative concepts being supported by DOE's Office of Fusion Energy Sciences, concurrent with its funding of tokamak research. (The Lawrence Livermore spheromak research is also supported by the Laboratory Directed Research and Development program.)

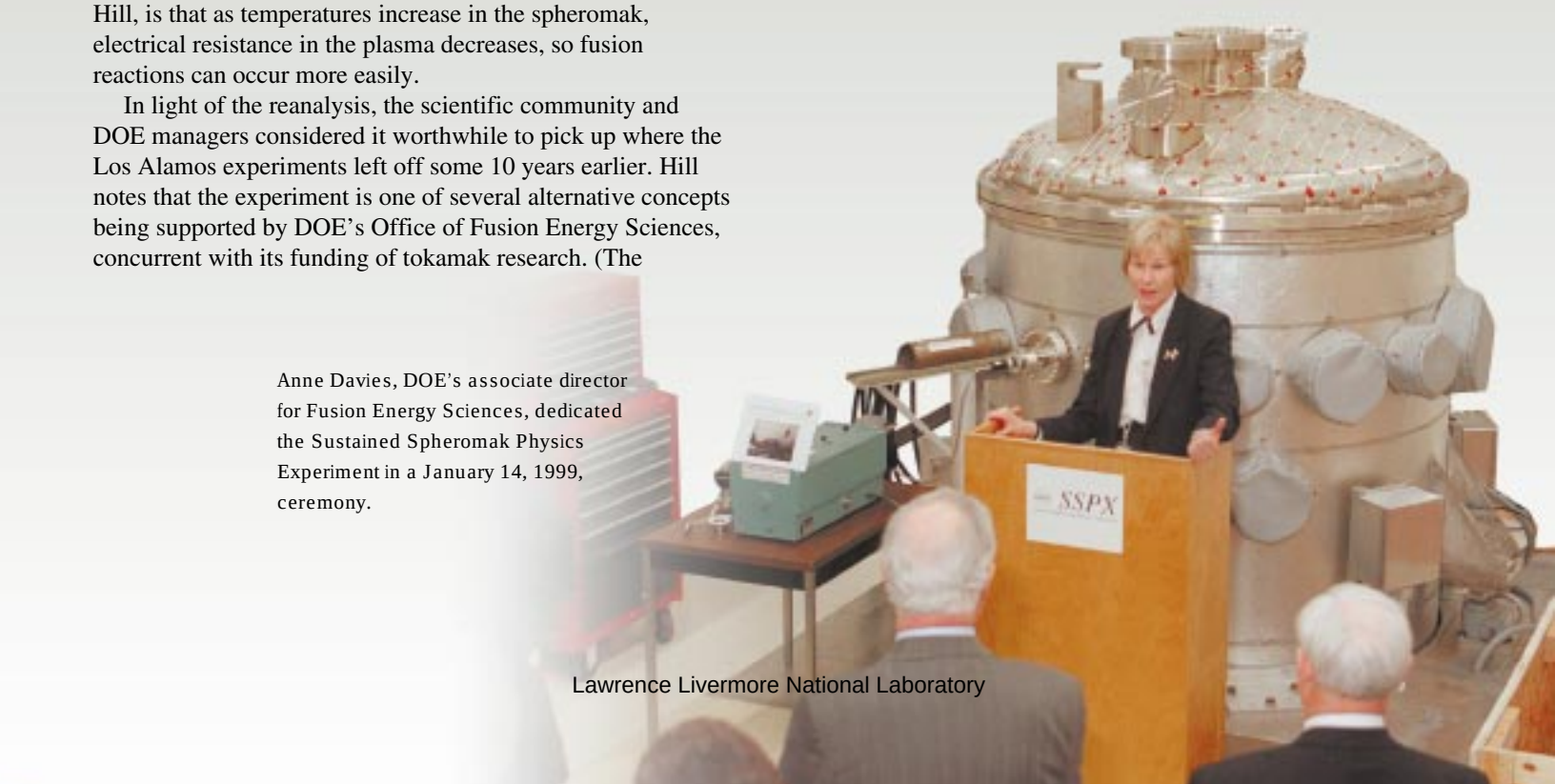
The overall goal of SSPX is to better understand spheromak physics by studying how magnetic fluctuations affect confinement. The experiments are designed to reach plasma temperatures of about 4 million degrees Celsius, similar to what the Los Alamos experiments obtained. Although this temperature is some 25 times cooler than that necessary to achieve fusion, it is sufficiently hot that energy is lost by processes similar to those that would occur in a fusion reactor. The experimental team will also attempt to keep the dynamo maintained in a hot plasma for 2 milliseconds instead of the 0.5 milliseconds achieved at Los Alamos.

The team is in the early phases of the project and is performing activities such as learning how to form the deuterium plasmas, achieving vacuum conditions, removing plasma impurities, and debugging diagnostic instruments.

Measuring Hot, Moving Currents

The experiments involve injecting deuterium plasma into a reactor's 1-meter-diameter by 0.5-meter-high vacuum vessel. A 10-kilovolt, 0.5-megajoule startup capacitor bank supplies a voltage across two electrodes to form the deuterium plasma. A separate 5-kilovolt, 1.5-megajoule power system sustains the plasma for 2 milliseconds. During this brief moment, the plasma balloons down into the vessel, forming a hot, moving circular current of ions that creates magnetic fields, which in turn induce more current within the plasma.

Improving the understanding of spheromak physics requires accurate measurements of plasma density, temperature, turbulence, and magnetic field fluctuations. Because probes inserted into the plasma would disrupt the



Anne Davies, DOE's associate director for Fusion Energy Sciences, dedicated the Sustained Spheromak Physics Experiment in a January 14, 1999, ceremony.

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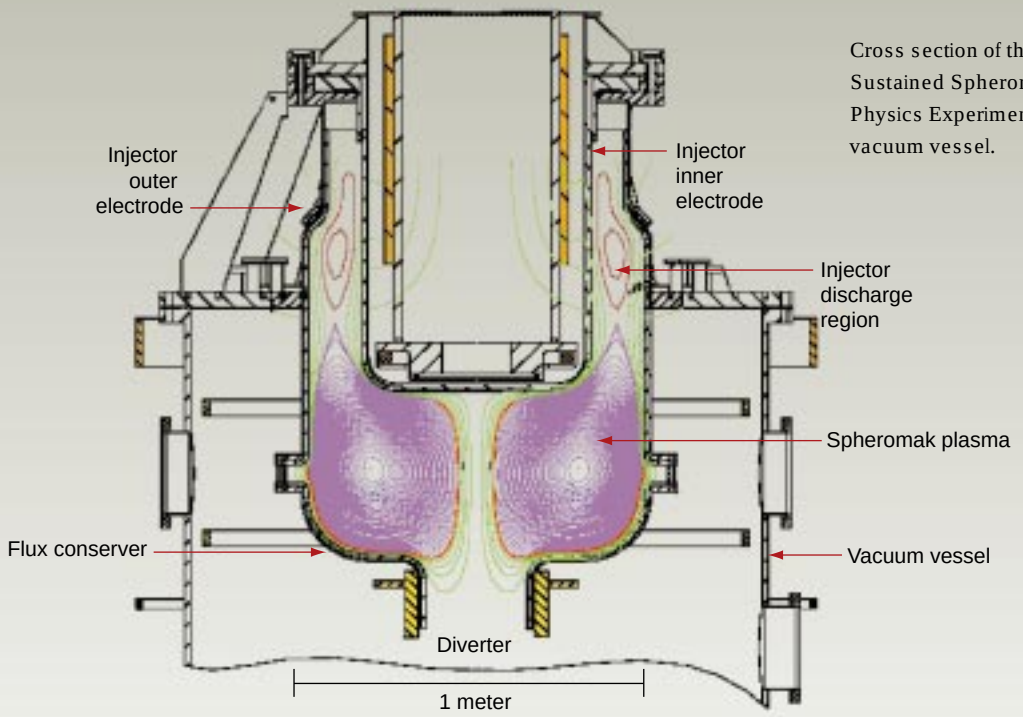

Cross section of the Sustained Spheromak Physics Experiment (SSPX) vacuum vessel.

experiments, the researchers must rely on remote measurements taken through a slot located around the spheromak's center.

One measurement instrument, called a reflectometer, was designed by scientists at Lawrence Livermore and the University of California at Davis. It yields profiles of the magnetic field strength by injecting waves of varying polarized light into the plasma. The reflected waves carry information about the changing plasma density and the magnetic fields. Another measurement instrument injects a glass pellet across the plasma; a laser views the pellet and determines the magnetic field from the reflected light.

Hill notes that although situated at Livermore, the SSPX work benefits from contributions from colleagues at Los Alamos, Sandia, General Atomics, California Institute of Technology, University of California at Berkeley and at Davis, University of Wisconsin, University of Washington, and Swarthmore College. He adds that SSPX also benefits from the wealth of information about plasmas that has been gained from the past decade of tokamak studies.

In light of the extensive collaborations with researchers from other institutions, the experiment control room is equipped with video cameras that permit collaborators to view experiments remotely from their computers. The video cameras are part of a system developed by Livermore researchers to link magnetic fusion experimental sites nationwide.

If the results from SSPX are sufficiently promising, the research team will develop a larger, follow-up experiment. This experiment would aim at achieving much hotter, longer lasting plasmas.

Clearly, many experts are speculating that the method nature chooses to confine plasmas in space may well be the process scientists should mimic in designing a fusion reactor to generate electricity on Earth.

—Arnie Heller

Key Words: CORSICA, deuterium, dynamo, magnetic fusion energy, plasma, spheromak, Sustained Spheromak Physics Experiment (SSPX), tokamak.

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