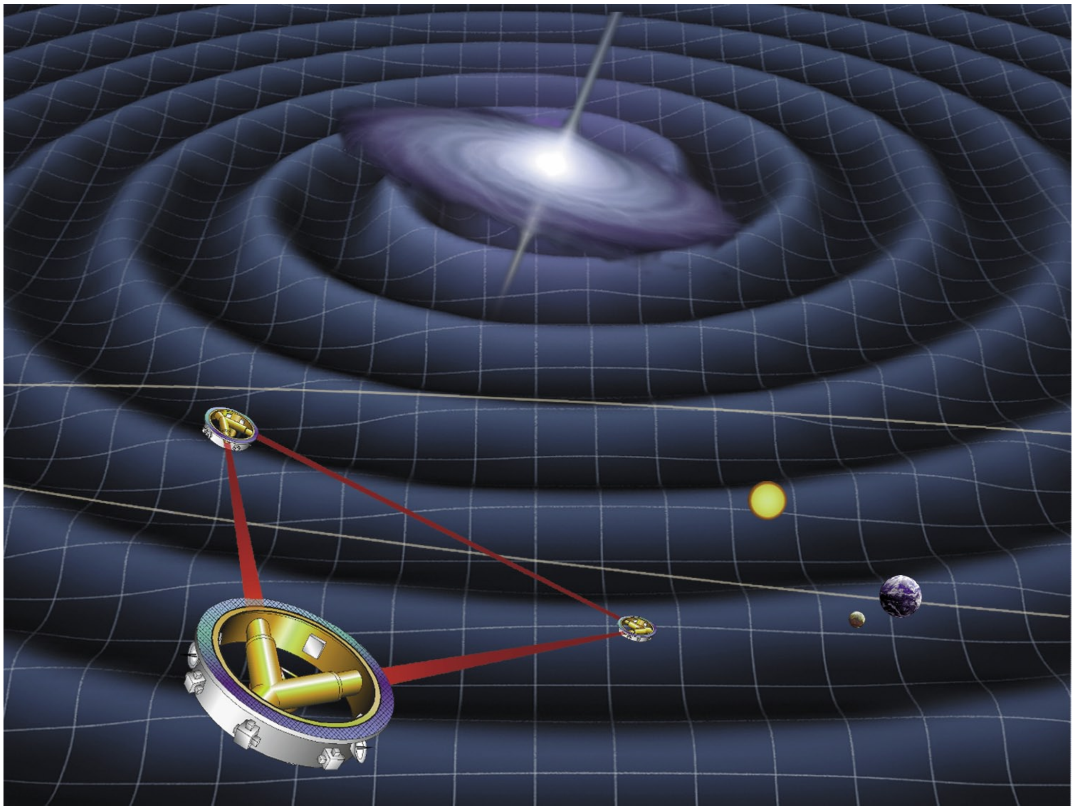


LISA will measure ripples in space-time.

A Space-time Symphony

If you could hear the sounds of space and time, the universe would be a noisy place. When those bizarre, light-bending, space-curving, and time-warping objects—black holes, neutron stars, and white dwarfs—meet, mingle, and merge, they disturb the fabric of space-time, sending ripples of gravitational waves across the cosmos. But it's not just black holes and their brethren that create these waves. The Big Bang itself, and maybe even more exotic objects called cosmic superstrings, all make their own undulations of space-time.

Although first predicted by Einstein's theory of general relativity in 1916, gravitational waves have yet to be detected. While scientists hope ground-based observatories like the Laser Interferometer Gravitational-Wave Observatory (LIGO), run by Caltech and MIT, will identify a signal soon, detection is virtually guaranteed by the much-anticipated Laser Interferometer Space Antenna (LISA). LISA will aim at much lower frequencies than LIGO, and will be capable of detecting more sources. When launched, it will be the only instrument of its kind in space, a mission that will observe the universe as never before, listening to the cosmic cacophony that so far has been silent to us.

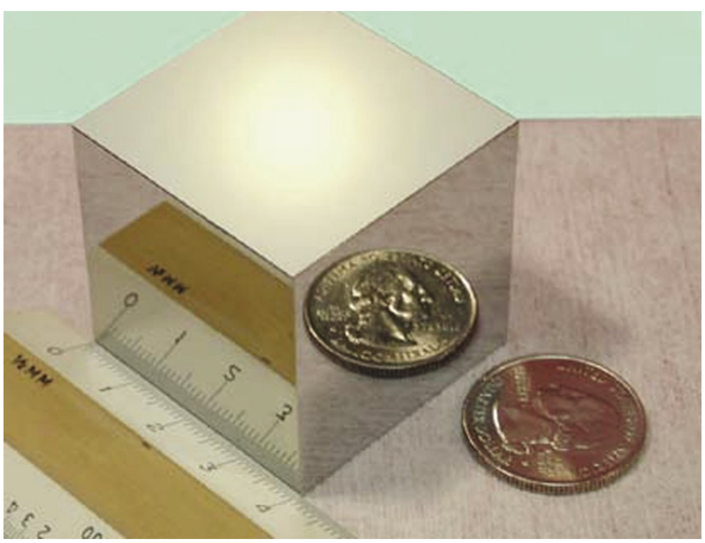
Gravitational waves are vibrations of space-time itself, and they jiggle everything they pass through, such as a planet or spacecraft—similarly to how sound waves jiggle the tiny bones in your ear, allowing you to hear. Unlike most telescopes, which point in a certain direction to detect signals, gravitational-wave detectors such as LISA measure waves from all directions, as an ear does. In this way, detecting gravitational waves is like hearing, and with so many potential sources out there, the trick is to figure out which is the black hole and which is the white dwarf. "It's like listening to an orchestra and trying to tell which is the cymbal and which is the flute, or which is the first violin and the second violin," says E. Sterl Phinney (BS '80), professor of theoretical astrophysics, chair of the LISA Science and Sources Working Group, and the leader of the team that developed NASA's Beyond Einstein program. LISA will address a myriad of topics, from the astrophysics of black holes to particle physics, to fundamental mysteries about the birth of the universe and the nature of gravity. In September, the National Research Council, which provides science policy advice for the government, recommended that LISA be made the flagship mission of the Beyond Einstein program.

Among the more promising phenomena the spacecraft will study is the merging of supermassive black holes. These events are some of the most violent and powerful in the universe, and likewise produce some of the strongest gravitational waves. When two of these behemoths meet, they spiral in toward each other. According to astronomers, nearly every galaxy has a supermassive black hole at its center, and when galaxies collide, the central black holes often merge—which can happen somewhere between once and 300 times per year.

Astronomers are finding that the evolution and formation of galaxies are inextricably tied to their merger history and to their central supermassive black holes. But since their black holes are always shrouded in gas, dust, and stars, scientists can't directly observe them. Gravitational waves, however, zip through everything at the speed of light, and with LISA, researchers would be able to make the first direct observations of merging black holes. "They will tell us something very fundamental about how galaxies evolved," says Tom Prince, professor of physics, the U.S. mission scientist for LISA and cochair of the LISA International Science Team.

LISA should also be able to detect a supermassive black hole eating a relatively tiny one, a few times the mass of our sun. But because the stellar-mass black hole is millions to billions of times smaller than the supermassive one, it works as what physicists call a "point test mass." As the smaller black hole circles its giant partner, it follows every curve of spacetime. The gravitational waves betray its path, telling physicists how space-time bends around the supermassive black hole. For the first time, physicists would find out if black holes behave as they think they do, Phinney says.

Merging supermassive black holes could also serve as the most accurate yardsticks yet of the universe. A black hole binary system, in which two black holes orbit each other, loses energy as it produces gravitational waves. The strength of the waves reflects how much energy is lost. As the system loses energy, the two black holes spiral closer together, spinning around each other faster and faster, increasing the system's orbital frequency. How quickly the orbital frequency changes tells scientists how fast the system is losing energy, which then tells them how strong the gravitational waves are. Just as light looks dimmer with greater distance, the strength of detected gravitational waves drops if the source is farther away. By comparing the measured strength of gravitational waves with the theoretical value, researchers can figure out how far away the system is. If the two black holes are coupled with an electromagnetic source, such as when the black hole eats surrounding gas and dust, LISA will make the most accurate measurements yet of the universe's expansion. Measuring cosmological expansion means measuring dark energy, the mysterious stuff that makes up roughly 70 percent of the universe. "LISA could revolutionize dark-energy studies," Prince says.



At the heart of LISA are the free-floating test masses like this one. Tiny shifts in distances between the test masses would mean a gravitational wave is passing through. The cubes' polished surfaces reflect lasers between the spacecraft to measure the shifts.

Furthermore, gravitational echoes of the Big Bang give astrophysicists a powerful way to study the universe during its first second of existence. Conventional observations, by way of electromagnetic waves—light—only allow researchers to look back to when the universe was 300,000 years old. Before then, the universe was a hot plasma soup, too thick for light to pass through. But because gravitational waves can pass through the primordial soup, LISA may be able to reveal the universe in its infancy.

But wait, that's not all. One of the more exotic gravitational-wave sources could be vibrating cosmic superstrings, long, one-dimensional objects that stretch across the universe. Waves on those strings, which were produced during the Big Bang, would move at the speed of light. They would flop around like a loose garden hose, creating gravitational waves, Phinney explains. If these strings exist and are detected, they would be a great discovery, he says. "It's something of a long shot, but it's a really exciting opportunity."

While the science promises to excite and amaze, the spacecraft is a remarkable feat of engineering in and of itself. LISA consists of three identical spacecraft in a triangular formation. In order to detect the frequencies researchers want, the triangle has to be gigantic—five *million* kilometers per side, or the same distance you'd cover if you drove to and from Pasadena and New York about 1,120 times. Each craft holds two identical instruments, and each instrument encases a shiny, free-floating, four-centimeter cube that acts as a test mass. Laser beams that bounce between a cube in one craft and a cube in another form the three sides of the triangle. When a gravitational wave zips by, it shifts the distance between the test masses by a tiny amount. The laser beams also shift, giving scientists a measurement of the gravitational wave. The shifts in distance are so small that the instrument needs to be accurate to 10 *pico*meters—smaller than any atom. Meanwhile, all this is trailing Earth by 20 degrees of its orbit around the sun, a distance equivalent to 25 million kilometers.

One of the biggest challenges engineers had to overcome was that of designing a spacecraft that would protect the test mass and keep it in its smooth orbit. Given the extreme sensitivity of the instrument, normally negligible effects such as the force from sunlight and the gravitational field of the spacecraft itself must be accounted for. One solution was to install microthrusters to counteract every inadvertent bump.

In 2010, the LISA Pathfinder mission will test this delicate ensemble. The mission, led by the European

Space Agency and with JPL supplying the thrusters, will test the technology in a true zero-gravity environment. There's no environment on Earth that's as quiet as the space environment that LISA will experience, Prince says. So to make sure that researchers understand how the instrument works, they have to send a prototype into space.

The real LISA, a collaboration between NASA and ESA, won't fly until 2018 at the earliest. The greatest hurdle so far, Phinney says, is whether NASA will provide enough funding. "The two big questions are when it will happen and whether the U.S. will have a major role in it," Phinney says, noting that the U.S.—and Caltech in particular—has been a scientific leader for LISA over the past couple decades. "It would be a shame if the U.S. were to just drop out of it."

Funding and politics aside, the science of LISA sells itself, drawing enthusiastic supporters, Phinney says. Scientists are confident the mission will eventually launch. When it does, scientists can finally tune in to the universe and its space-time symphony. □—*MW*

Mars Rovers: The Next Generation

NASA scientists are seeking big pieces of an even bigger puzzle to help answer the biggest question about Mars—was it ever, is it, or could it possibly be a place for life to exist?

The size of a Mini Cooper and having more instruments than any previous Mars rover, the one-ton Mars Science Laboratory (MSL) will find some of those pieces. Expected to launch in September 2009, it will land in the summer of 2010. During the planned mission, which should last one Martian year (almost two Earth years) it will travel 20 miles.

"We're hoping that the Mars Science Lab will be able to go much further and last much longer than we anticipate, as the rovers Spirit and Opportunity have," says project scientist John Grotzinger, who came to Caltech in 2005, after years at the Massachusetts Institute of Technology. Those two rovers are still roaming Mars after landing in 2004; they were originally expected to last 90 Martian days.

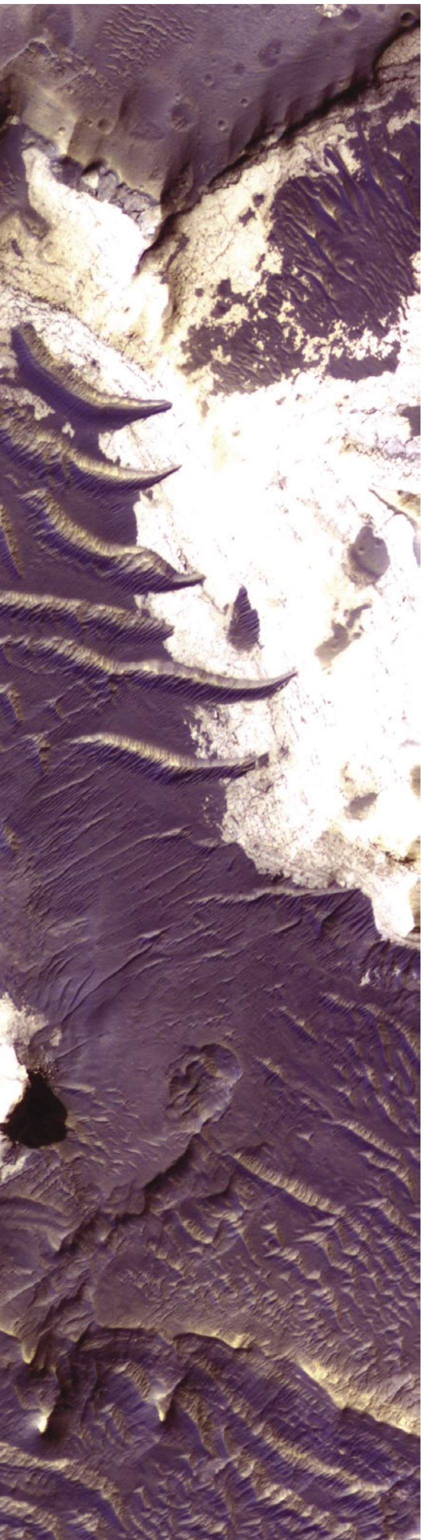
MSL will be fueled by nuclear power, so it will not be as restricted in its operations as the previous solar-powered rovers have been. The MSL can reach higher latitudes that get less sunlight each day. Previous rovers had to land within 20 degrees of the equator, but MSL should be able to get 10 degrees closer to the poles. At a conference in late October, the original 36 proposed landing sites were narrowed down to six sites and four alternates, all of which are ±30 degrees of Mars' equator. The farthest poleward proposed site is Terby Crater, at about 27.5 degrees south latitude.

MSL will pioneer a technique called "steered landing" that will get it as close as possible to its selected site. The previous rovers bounced and rolled in their protective airbags, giving little control over where they landed within their 50- to 100-kilometer target ellipse.

"It's still not perfect, but now we can land within the range of a city rather than an

This engineering model of the Mars Science Laboratory's chassis, dubbed "Scarecrow" because it does not have a brain of its own, makes its way down a hill in JPL's Mars Yard. MSL will be about twice as long and four times as heavy as the current Mars rovers, Spirit and Opportunity.

One proposed MSL landing site, Holden Crater, lies at 26.8 degrees south latitude. Seen here in enhanced color, Holden contains deep gullies carved by running water, as well as putative lake-bed deposits. One of the latter is shown here—the bright material at the base of the cliff.



entire county," says Deputy Project Scientist Ashwin Vasavada.

MSL is equipped with small rockets that fire downward for a few seconds at a time to control landing speed. The shape of the craft also allows the entry, descent, and landing team to control the angle of attack, which determines the lander's lift and forward velocity. MSL knows its desired trajectory, and sensitive gyroscopes allow it to correct itself, should something push it off course. These tools will shrink the landing ellipse to a mere 10 kilometers or so.

"Mars is now a place for sedimentologists," says Grotzinger, the Jones Professor of Geology. "Using the same techniques to see what the early earth was like, we can find out what Mars was, and is, like." On a table in his office sits a large rock from Australia, whose surface bears ripples that look just like the wave patterns that form in sand at the beach, where the tide ebbs and flows. Scientists have already seen ripples like these on Mars, implying that water once flowed there.

But now scientists are going beyond water, seeking compounds containing carbon, hydrogen, nitrogen, phosphorous, and sulfur, all essential ingredients for life, as well as various minerals that may indicate organisms that metabolized these compounds. A suite of instruments named Sample Analysis at Mars (SAM), provided by NASA Goddard, will analyze samples of material collected by MSL's robotic arm. SAM includes a gas chromatograph and mass spectrometer that will analyze rock and soil samples. A tunable laser spectrometer will determine the ratios of key isotopes in the air, providing clues to the history of Mars' atmosphere and water.

An X-ray diffraction instrument called CheMin, built by JPL, will identify and analyze minerals in rocks and soil. Previous Mars rovers have used spectroscopy to identify elements, but X-ray diffraction is far less ambiguous. "For understanding geologic history, this is especially important," says Vasavada. "The same chemical elements will take the form of different minerals depending on the environment in which they were formed."

These minerals arrange the same atoms into different crystal structures, meaning that the atoms have different three-dimensional spacings. A beam of X rays shot into each different structure will thus be diffracted at a different set of angles. Due to its bulk and weight, an X-ray diffractometer has never been put on a spacecraft before, but CheMin is about the size of a laptop computer bag.

MSL will be the first rover ever equipped with its own light sources. An ultraviolet light will be used to make minerals fluoresce, like the glow-in-the-dark geology displays at many science museums. This isn't being done to make trippy pictures—the fluorescence spectrum will help identify the minerals in the rocks.

Mounted on the rover's arm, the lights are part of the Mars Hand Lens Imager (MAHLI), which will take extreme close-up pictures of rocks, soil, and perhaps ice, revealing details smaller than the width of a human hair. MAHLI's color pictures will have a higher resolution than the Microscopic Imagers on Spirit and Opportunity, which only take pictures in black and white. Using its zoom lens, MAHLI can also focus on objects that the arm cannot reach.

Like Spirit and Opportunity, MSL's Mast Camera will see the rover's surroundings in high-resolution color, and its multispectral capability allows rock and mineral types to be identified in the landscape from afar. What's new is the capability to take and store high-def video—in stereo, no less! Now we'll be able to watch dust devils form and whip by in 3-D. MastCam has its own internal image storage, processing, and compression, taking this computationally intensive burden off the rover's main brain.

Another camera, called the Mars Descent Imager (MARDI), will take pictures as the MSL lands.

MAHLI, MastCam, and MARDI are being built by Malin Space Science Systems of San Diego, headed by Michael Malin (PhD '76).

The ChemCam, a collaboration between France and the U.S., will use laser pulses to vaporize thin layers of material from Martian rocks or soil from up to 10 meters away. A spectrometer will then identify the newly liberated atoms, and a telescope will capture detailed images of the area illuminated by the beam. ChemCam and MastCam will both sit on the rover's head-high mast, helping researchers decide which objects they should investigate next.

The rover's Radiation Assessment Detector, provided by the Southwest Research Institute, will provide crucial information for planning human exploration of Mars, and for assessing the planet's ability to harbor life.

Canadian researchers are also getting in on the action. The Canadian Space Agency will be providing the Alpha Particle X-ray Spectrometer, which will be located on the arm, and will determine the relative abundances of different elements in rocks and soils.

Russia's Federal Space Agency is providing the Dynamic Albedo of Neutrons instrument to measure subsurface hydrogen up to one meter below the surface.

This method has been used on JPL's Mars Odyssey to map subsurface water from orbit, but this is the first time a neutron spectrometer will land on the surface for a close-up look.

Finally, Spain and Finland are taking part with the Rover Environmental Monitoring Station to measure atmospheric pressure, temperature, humidity, winds, and ultraviolet radiation levels.

Like any other project, this mission has faced challenges. "We're in the sausage-making stage of it right now," said Project Manager Richard Cook, referring to the aphorism attributed to Otto von Bismarck, "Laws are like sausages. It's better not to see them being made."

Grotzinger was faced with the first of these challenges about six months ago when he took over Edward Stolper's position as project scientist. (Stolper, the Leonhard Professor of Geology, had been appointed Caltech's provost, and was unable to give MSL the time it deserved.) In the same week Grotzinger joined MSL, he was told that the project was $75 million over its original budget of $1.7 billion.

Grotzinger needed to cut costs but keep the science program strong. None of the rover's instruments have been removed from the payload, but some engineering changes have been made. These include reductions in design complexity—for example, a rock-grinding tool has been changed to a rock-brushing tool, and MastCam's zoom capability got scrapped. There will also be fewer spare parts, simplified flight software, and some ground-test program changes.

MSL will address the puzzle of life on Mars, but the answers won't come easily, Grotzinger says. "Like most things in science, there's not a silver bullet." □—*JS*

NuSTAR ReNued

NASA has given the go-ahead to bring a mission back from the dead. Although they cancelled it in 2006, officials have revived the Nuclear Spectroscopic Telescope Array, or NuSTAR. The spacecraft will be the most capable instrument yet to explore the universe using high-energy X rays.

"It's great that NASA was able to restart the mission," says Fiona Harrison, professor of physics and astronomy and NuSTAR principal investigator. "I'm incredibly excited about our planned science program, as well as the unanticipated things we are bound to discover with a new telescope this sensitive." NASA had scrapped the mission due to funding pressures within the Science Mission Directorate, but NuSTAR will now proceed to flight development, with an expected launch in 2011.

Researchers designed the mission to answer some fundamental questions about the universe: What powers the most extremely active galaxies? How were the heavy elements of the universe created? How are black holes distributed through the cosmos? NuSTAR will have more than 500 times the sensitivity of previous instruments that looked for black holes.

The members of Harrison's team have been working on NuSTAR technology for more than 10 years, developing optics that can focus high-frequency X rays for the first time. X rays are at the high-energy end of the electromagnetic spectrum, and easily penetrate most materials—which is why doctors use them to see through skin and flesh. X rays can only be reflected and focused in a telescope if they hit the mirror at a shallow angle, like rocks skipping on a pond. But since they hit the mirror nearly end-on, it has a very small collection area. In order to catch as many as possible, X-ray telescopes have several nested mirrors called shells. NuSTAR will have two such multiple-mirror systems, each with 130 cylindrical shells of reflective material. The system was demonstrated on a balloon-borne experiment called HEFT, for High Energy Focusing Telescope, that Harrison's group flew in 2005.

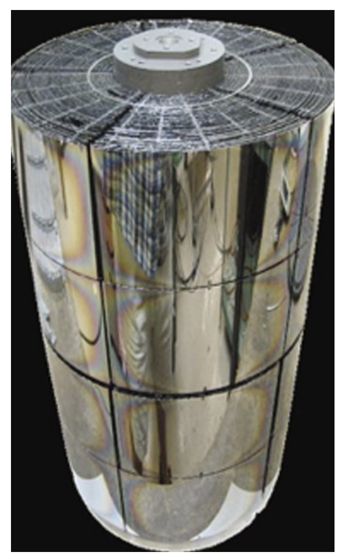
Each of the 130 shells is coated with an average of 300 thin layers of alternating high- and low-density materials of varying thicknesses, in order to reflect a whole spectrum of X rays. Other X-ray observatories, such as Chandra or the European Space Agency's XMM-Newton, don't have these multilayer coatings, which limits them to low-energy X rays.

NuSTAR's X-ray detector is a special CCD, or charge-coupled device, analogous to the one in your video camera. But this one, developed by Harrison's goup in Caltech's Space Radiation Lab, is made of cadmium zinc telluride.

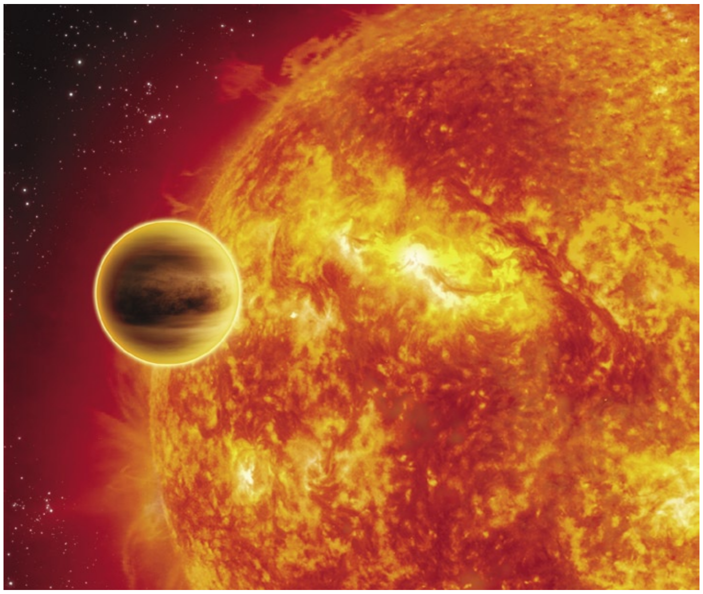
NuSTAR also incorporates an extendable structure developed by JPL and Alliant Techsystems Inc. for the Shuttle Radar Topography Mission that will fit the telescope into a small, inexpensive launch vehicle. Once in orbit, the arm will be extended to move the mirrors some 10 meters away from the detector, bringing the X-ray universe into focus.

In November 2003, NuSTAR was one of six proposals selected from 36 submitted to NASA's Small Explorers Program, which funds lower-cost, highly focused, rapidly developed scientific spacecraft.

NASA anticipates that NuSTAR will bridge a gap in astrophysics missions between the 2009 launch of the Wide-Field Infrared Survey Explorer and the 2013 launch of the James Webb Space Telescope. Besides using high-energy X rays to map areas of the sky, the spacecraft will complement astrophysics missions that explore the cosmos in other regions of the electromagnetic spectrum. □—*EN*



HEFT's mirror system has 72 shells. NuSTAR's will be nearly identical, but bigger and with 130 shells.



An artist's conception of HD 189733b in orbit around its star.

Hot and Steamy

It may not be the water-world that fields Kevin Costner's dreams, but the exoplanet HD 189733b has been found to have water vapor in its atmosphere. This observation provides the best evidence to date that water exists on worlds outside our own solar system.

The discovery was made by NASA's Spitzer Space Telescope, which possesses a particularly keen ability to study nearby stars and their planets. HD 189733b lies 63 light-years away.

"Water is the quintessence of life as we know it," says Yuk Yung, professor of planetary science and one of the authors of the study published in the July 12 issue of *Nature*. "It is exciting to find that it is as abundant in another solar system as it is in ours."

HD 189733b swelters as it zips around its star every two days or so. Astronomers had predicted that planets of this class, termed "hot Jupiters," would contain water vapor in their atmospheres, yet evidence has been hard to come by. "We're thrilled to have identified clear signs of water on a planet that is trillions of miles away," says lead author Giovanna Tinetti, a European Space Agency fellow at the Institute d'Astrophysique de Paris in France and former postdoc at Caltech's Virtual Planetary Laboratory.

Coauthor Mao-Chang Liang (PhD '06) of Caltech and the Research Center for Environmental Changes in Taiwan adds, "The discovery of water is the key to the discovery of alien life."

Wet hot Jupiters are unlikely to harbor any creatures. Previous Spitzer measurements indicate that HD 189733b is a fiery 1,000 degrees Kelvin on average. Ultimately, astronomers hope to use instruments like those on Spitzer to find water on rocky, habitable planets like Earth. "Finding water on this planet implies that other planets in the universe could also have water," says coauthor Sean Carey of the Spitzer Science Center, which is headquartered at Caltech.

A team of astronomers had found hints of water on another planet called HD 209458b by analyzing visible-light data taken by NASA's Hubble Space Telescope. The Hubble data were captured as the planet crossed in front of the star, an event called the primary eclipse. Tinetti and her team used changes in the star's infrared light as the planet slipped by, filtering the starlight through its outer atmosphere. The astronomers noticed that at each of three different wavelengths, a different amount of light was absorbed—a pattern matching that created by water. "Water is the only molecule that can explain that behavior," Tinetti says. "Observing primary eclipses in infrared light is the best way to search for this molecule."

The water on HD 189733b is too hot to condense into clouds; however, previous observations by several telescopes suggest that it might have dry clouds, along with high winds and a hot, sun-facing side that is warmer than its dark side.

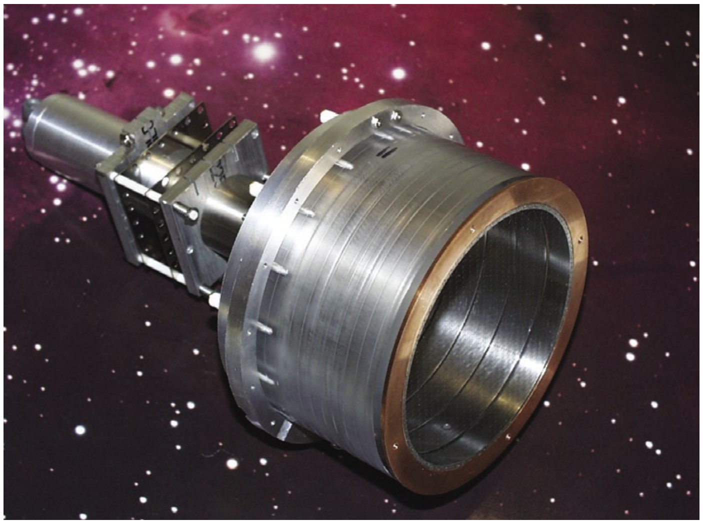
Other authors of the paper include Alfred Vidal-Madjar, Jean-Phillippe Beaulieu, David Sing, Nicole Allard, and Roger Ferlet of the Institute d'Astrophysique de Paris; Robert Barber and Jonathan Tennyson of University College London in England; Ignasi Ribas of the Institut de Ciències de l'Espai, Spain; Gilda Ballester of the University of Arizona, Tucson; and Franck Selsis of the Ecole Normale Supérieure, France. □—*RT*

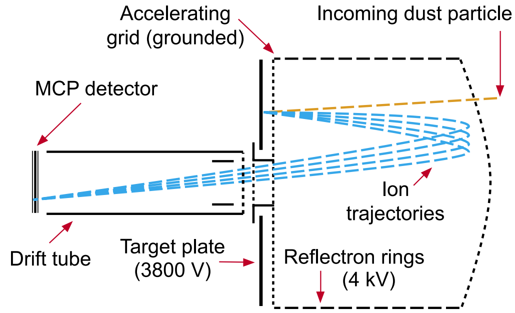
Cosmic Dust in the Wind

Don't let its seemingly vast emptiness fool you: the universe is a dirty place. Comets, supernovae, and solar winds spew microscopic particles of matter, called cosmic dust, across the universe. Instead of being a filthy nuisance, this cosmic dust may hold clues about the history of the solar system and the origins of life on Earth. "Origins, that's a big word at NASA these days," says Jesse (Jack) Beauchamp (BS '64), the Ferkel Professor of Chemistry. Along with Thomas Ahrens (MS '58), the Jones Professor of Geophysics, Emeritus, Beauchamp has built a device to extract cosmic dust's secrets. They call their creation the Dustbuster, and they hope it will be put on a future mission to the outer planets.

Unlike the Dustbuster you may have in your car or broom closet, this gadget isn't a vacuum; it's a mass spectrometer. On Earth, chemists, biologists, and those CSI guys use mass spectrometers to identify unknown molecules. It works on the principle that when a molecule or atom is charged, or ionized, its behavior in an electric or magnetic field will depend, partly, on its mass.

Cosmic dust flows through the outer reaches of our solar system at speeds of 10 to 80 kilometers per second. Any particles hitting a target plate on the Dustbuster are instantly vaporized, and the energy of the impact strips electrons from the molecules,





As the Dustbuster (left) flies through space, dust particles entering its maw (above) smash into a target plate that fragments them into positively charged ions and free electrons. The rebounding positive ions are given a uniform "kick" to the left by the accelerator grid and are then steered into the detector by means of an electric field created by the reflectron rings.

producing positively charged ions with various amounts of kinetic energy. Inside the Dustbuster, the ions are accelerated by an electric field and guided towards an ion detector through a part called the reflectron. This part negates any differences in kinetic energy between the ions produced by the impact. Since the electric field provides each ion with the same amount of energy, the time it takes each ion to reach the detector will depend on its mass. It's an ionic drag race—imagine a Honda Civic dueling a Hummer powered by a Civic engine. Just as the heavier Hummer will move more slowly, heavier ions will accelerate to lower velocities than lighter ions. Faster, lighter ions will arrive at the detector first, so monitoring when ions reach the finish line determines their masses.

"There's quite a history of using mass spectroscopy in space exploration, from the Viking program onward," says Beauchamp. On the recent Cassini-Huygens mission to Saturn, data from the Cassini Dust Analyzer (CDA) showed that Saturn's outer ring was formed from dust spraying off of the south pole of its moon, Enceladus. "Having seen the CDA, we were inspired to see if we could build something that was smaller in size, used less power, but had high performance," says Beauchamp. While the CDA is 17 kilograms and 1 meter long, the Dustbuster is only about 0.5 kilograms and 20 centimeters long. Two types of Dustbusters have now been built and tested: Dustbuster I is designed to sample cosmic dust found streaming through the solar system, while Dustbuster II is designed to sample the high flux of dust from comet tails.

How can something as simple as the mass of a molecule found in a tiny dust particle tell us about the history of our solar system? Cosmic dust's journey often begins in distant stars, from which it is shot out across the galaxy through their solar winds or, more dramatically, a supernova. Some cosmic dust accumulates inside interstellar clouds that become unstable and collapse, forming new stars and planets. Much of our solar system, including the matter in your own body, was once cosmic dust particles flying through the galaxy.

A dust particle's composition can be read like a passport. Inside stars, many of the heavier elements, like carbon, oxygen, and iron, are forged from lighter elements, like hydrogen and helium, through a process called nucleosynthesis. (Caltech physics professor Willie Fowler, PhD '36, won the Nobel Prize in Physics in 1983 for working out the details.) Isotopes of the elements—atoms that have the same number of protons, but a different number of neutrons—are also created through nucleosynthesis. Depending on the type of star and its stage in life, nucleosynthesis will produce different mixes of elements and isotopes, so by analyzing the cosmic dust, scientists can learn about the evolution of stars. Organic, carbon-based molecules are synthesized as the dust flies through different chemical environments in space, like on the tails of comets. Scientists are very interested in these, as such molecules may have served as precursors to DNA, amino acids, and other biological molecules on Earth.

Besides Beauchamp's work on the Dustbusters, he has also been working on a return visit to Saturn's moon Titan. "We have been heavily involved with looking at Titan as a model for early Earth," says Beauchamp. Lab experiments that simulate conditions on Titan and data from the Huygens lander have confirmed the presence of simple organic molecules there. "'Astrobiological hotspot' is a term I like to use. It's where you suspect there are the conditions for emergent synthesis of organic molecules," says Beauchamp. Learning how this occurs on the surface of Titan could help explain how the molecules of life were first synthesized on Earth.

To study these astrobiological hotspots, any probe returning to Titan will need a mass spectrometer. "Mass spectrometers are extremely valuable tools for such missions," says Kim Reh at JPL. Reh was part of a team that submitted a proposal to NASA in October for a mission to "prebiotic" moons in the outer solar system, like Jupiter's moon Europa and Saturn's moons Enceladus and Titan. Beauchamp was a consultant to the team. "NASA intends to review the results of this study by the end of this year and select one or two of these science targets for further study in 2008. The longer-term goal is to select a mission in 2009," says Reh. □—*MT*

PICTURE CREDITS: 36, 38—NASA/JPL-Caltech; 39—NASA/JPL/Univesiy of Arizona; HEFT team; 41—C. Carreau, ESA; 42—Daniel Austin

A Chronology of JPL Spacecraft

Explorers 1-5 **Launch Dates: Jan.–Aug., 1958**
Explorers 1, 3, and 4 discovered and probed the Van Allen Belts.

Pioneers 3 and 4 **Dec. 6, 1958, and March 3, 1959**
Pioneer 4 became the first U.S. spacecraft in solar orbit.

Rangers 1-9 **1961–65**
Rangers 7-9 returned images until their planned moon impacts.

Mariners 1 and 2 **July 22 and Aug. 27, 1962**
The first to another planet, Mariner 2 studied Venus's atmosphere and surface, and measured the solar wind for the first time.

Mariners 3 and 4 **Nov. 5 and 28, 1964**
Mariner 4 took the first close-up photos of another planet, Mars.

Surveyors 1-7 **1966–68**
Surveyors 1, 3, and 5-7 were the first U.S. landings on the moon.

Mariner 5 **June 4, 1967**
Originally a backup Mars craft, Mariner 5 went to Venus.

Mariner 6 and 7 **Feb. 24 and March 27, 1969**
First dual mission to Mars; flew over the equatorial and south polar regions.

Mariner 8 and 9 **May 8 and 30, 1971**
Mariner 9 was the first successful Mars orbiter.

Mariner 10 **Nov. 3, 1973**
Pioneered the "gravity assist" concept, swinging by Venus en route to Mercury.

Vikings 1 and 2 **Aug. 20 and Sept. 9, 1975**
The first Mars landings. Each Viking had an identical orbiter and lander; all four spacecraft completed extended missions.

Voyagers 1 and 2 **Aug. 20 and Sept. 5, 1977**
They completed the Grand Tour of the solar system, and are now heading toward interstellar space.

Seasat **June 26, 1978**
Tested four radar instruments that studied Earth and its seas.

Solar Mesosphere Explorer **Oct. 6, 1981**
Traced the life cycle of ozone in the upper atmosphere.

Infrared Astronomical Satellite **Jan. 25, 1983**
An infrared telescope orbiting above Earth's atmosphere.

Magellan **May 4, 1989**
Mapped Venus's surface. Pioneered the aerobraking technique, using a planet's atmosphere to steer or slow down.

Galileo **Oct. 18, 1989**
Orbited Jupiter and dropped a probe into its atmosphere; made many flybys of its major moons.

Ulysses **Oct. 6, 1990**
A collaboration with the European Space Agency, Ulysses monitors the sun from an orbit around its poles.

Topex/Poseidon **Aug. 10, 1992**
A French-U.S. mission, it measured sea levels every 10 days with an accuracy of less than 10 centimeters.

Mars Observer **Sept. 25, 1992**
Lost shortly before arrival at the red planet.

Mars Global Surveyor **Nov. 7, 1996**
This orbiter operated longer than any other Mars mission.

Mars Pathfinder **Launch Date: Dec. 4, 1996**
The lander and its Sojourner rover explored an ancient flood plain called Ares Vallis.

Cassini-Huygens **Oct. 15, 1997**
A European-U.S. mission orbiting Saturn, Cassini sent the Huygens probe to Titan, Saturn's largest moon.

Deep Space 1 **Oct. 24, 1998**
Tested new technology and took photos of comet Borrelly's nucleus.

Mars Climate Orbiter **Dec. 11, 1998**
This interplanetary weather satellite was lost on arrival.

Mars Polar Lander/Deep Space 2 **Jan. 3, 1999**
Aiming for the edge of Mars' south polar cap and carrying twin soil probes (Deep Space 2), it was lost during final descent.

Stardust **Feb. 7, 1999**
Collected and returned a sample of dust from comet Wild-2.

Wide-field Infrared Explorer **March 4, 1999**
A small telescope that lost its cryogenic coolant soon after launch.

Quick Scatterometer **June 19, 1999**
Measures ocean wind velocities and directions.

Active Cavity Irradiance Monitor Satellite **Dec. 22, 1999**
Monitors the total amount of the sun's energy reaching Earth.

2001 Mars Odyssey **April 7, 2001**
Now orbiting Mars.

Genesis **Aug. 8, 2001**
Collected and returned samples of solar wind particles.

Jason 1 **Dec. 7, 2001**
A follow-up oceanography mission to Topex/Poseidon.

Gravity Recovery and Climate Experiment **March 17, 2002**
A U.S.-German mission consisting of two spacecraft flying together to measure Earth's gravitational field.

Galaxy Evolution Explorer **April 28, 2003**
A small ultraviolet telescope that studies galaxy formation.

Mars Exploration Rovers **June 10 and July 7, 2003**
The Spirit and Opportunity rovers continue to explore opposite sides of Mars.

Spitzer Space Telescope **Aug. 24–25, 2003**
A large infrared telescope. One of NASA's Great Observatories.

Deep Impact **Jan. 12, 2005**
Sent an impactor to smash into comet Tempel 1's nucleus.

Mars Reconnaissance Orbiter **Aug. 12, 2005**
Analyzing Mars's surface to bridge the gap between surface observations and measurements from orbit.

CloudSat **April 28, 2006**
Provides a never-before-seen 3-D profile of Earth's clouds.

Phoenix **Aug. 4, 2007**
A high-latitude lander en route to Mars equipped with a robotic arm to dig into layers with water ice.

Dawn **Sept. 27, 2007**
The first craft to orbit two bodies after leaving Earth. It will orbit Vesta and Ceres, two of the solar system's largest asteroids.