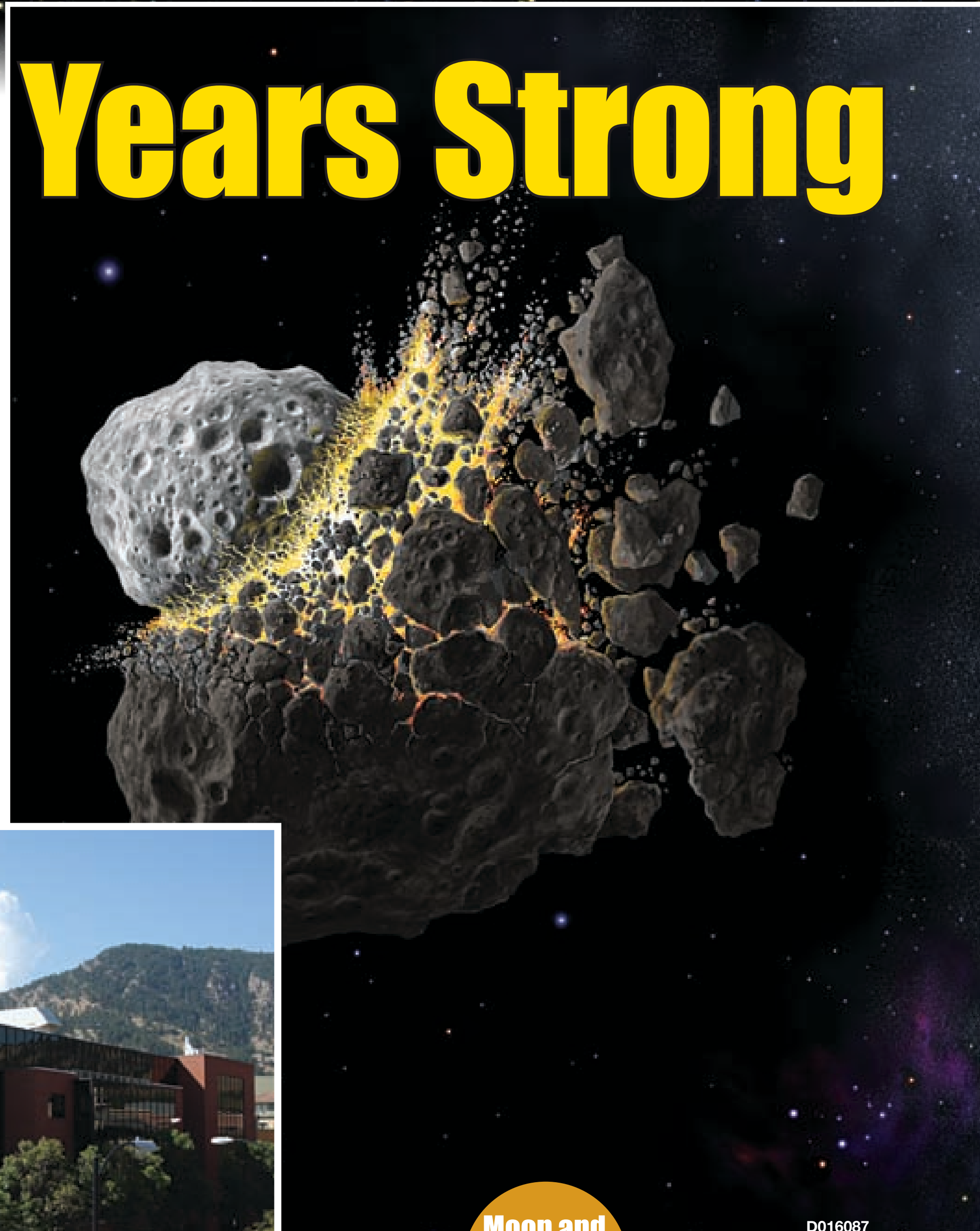
Fifteen Years Strong

SwRI's Planetary Science Directorate has built a worldwide reputation on investigating mysteries across time and space, from the death of the dinosaurs to a close-up look at Pluto



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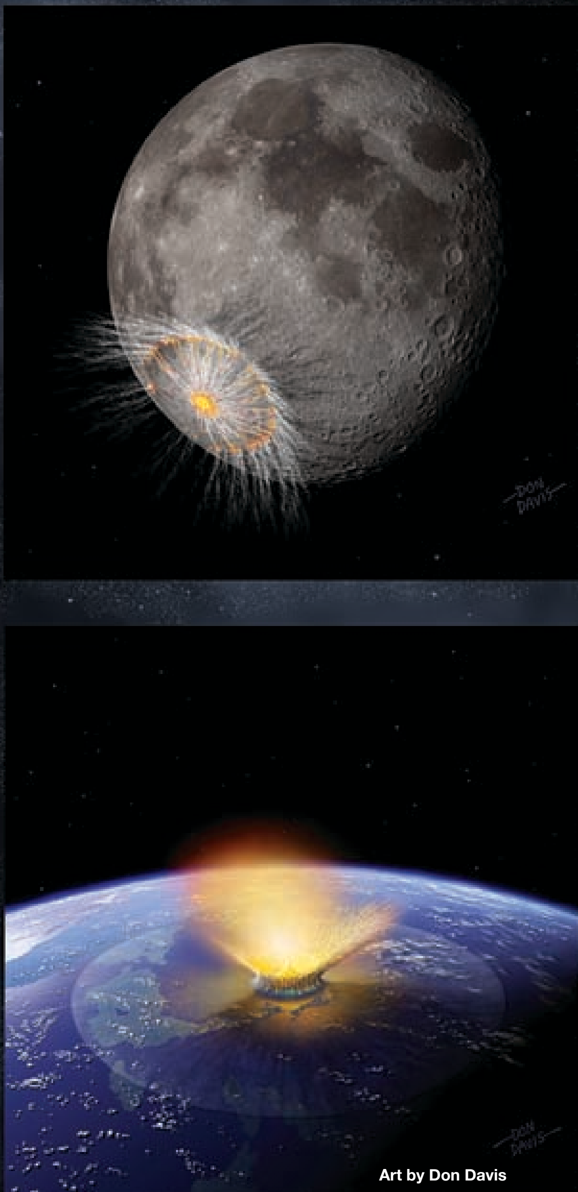
In 1994, Southwest Research Institute (SwRI) opened an office in Boulder, Colo., aimed at establishing a planetary astronomy research group in this scientifically fertile region at the base of the Rocky Mountains. At that time, the office comprised two scientists and a part-time administrative assistant. By its 15th anniversary in 2009, the staff had grown to more than 65 employees who study nearly every aspect of the solar system and related astronomical topics, lead and participate in space missions, develop instrumentation and conduct laboratory studies.

The Planetary Science Directorate has since established itself as a world-recognized center of planetary research. It hosts a steady stream of international visiting scientists and engineers, and organizes workshops and meetings with focused scientific and space exploration topics. This article highlights a sample of the diverse areas of research that evolved into large programs including moon and small body dynamics, the outer solar system, Mars, solar physics and space operations.

Moon and Small Body Dynamics

Space scientists at Boulder perform research spanning the evolution of small bodies, such as asteroids, comets, meteoroids and dust, to the formation of the planets and satellites like the Moon. The ultimate goal is to explore how and when the planet formed, why it has water and other conditions suitable for life, and whether it is possible that other Earth-like planets exist elsewhere. In essence, the exploration of how the solar system came to be is also a way to understand our place in the universe.

A particular topic of interest to both scientists and the public is the meteorite impact believed to have wiped out the



The impact believed to have caused mass extinctions on Earth 65 million years ago — including the dinosaurs — has been traced to the breakup of the parent of the family of objects associated with the asteroid Baptistina. This 170-kilometer-wide asteroid broke apart 160 million years ago and its fragments later showered the inner solar system.

dinosaurs and other life 65 million years ago. SwRI space researchers traced this impact back to a large breakup event in the main asteroid belt, a region of small bodies between Mars and Jupiter. Approximately 160 million years ago, the 170-kilometer-wide asteroid Baptistina was disrupted when it was struck by another large asteroid. This created a cluster of asteroids with similar orbits (known as the Baptistina family) that gradually spread to a nearby "superhighway" where they could escape the main asteroid belt and be delivered to orbits that cross Earth's path. The addition of so many new fragments to the inner solar system created an asteroid "shower" that matches up very well with the impact record on both Earth and the Moon over the past 120 million years or so.

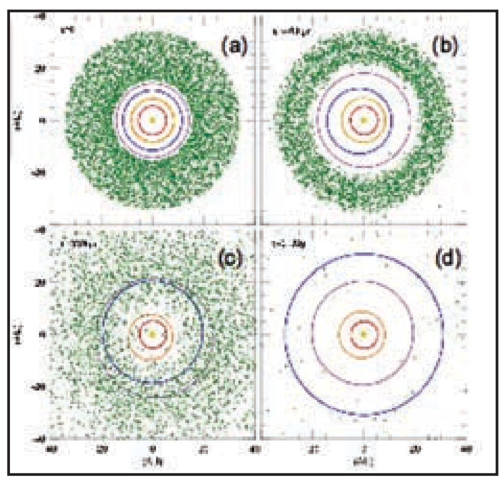
Close to the peak of this shower, a 10-km asteroid struck Earth and created the 180-km Chicxulub crater on Mexico's Yucatan Peninsula. Telltale clues from dynamical models, sediment samples and a meteorite from this time period give a 90 percent probability that the object forming the Chicxulub crater was a refugee from the Baptistina family. This work demonstrated that the collisional and dynamical evolution of the main asteroid belt may have significant implications for understanding the geological and biological history of Earth.

NASA awarded SwRI the Center for Lunar Origin and Evolution (CLOE), one of the first centers of the new Lunar Science Institute. The Moon is a unique extraterrestrial laboratory, because it is the only object that is both relatively accessible and still bears evidence from practically every period of solar system history. CLOE will investigate several lasting mysteries that were uncovered during the historic Apollo program.

A key project deals with the intense debate concerning the nature of the lunar impact record in the relatively short interval from 4 to 3.8 billion years ago, commonly referred to as the "Late Heavy Bombardment," or LHB. This phase in lunar history was dominated by large impact events — the remnant lava-filled basins that now shape the dark-colored "man in the moon" design on the lunar surface. Research by staff members suggests the LHB reveals the last and perhaps key phase of planet formation when the solar system may have rearranged itself.

In this model, the giant planets — Jupiter, Saturn, Uranus and Neptune — formed in a much more compact configuration than they have today. Just outside their orbits loomed a massive disk of comets. Gravitational interactions between the planets and the comet disk caused the planets to slowly migrate in space. Computer simulations indicate that, after hundreds of millions of years, Jupiter and Saturn reached orbits where their mutual gravitational kicks became quite pronounced. This triggered an instability that led to a violent reorganization of the outer solar system. Uranus and Neptune were pushed into the comet disk, scattering its members throughout the solar system. Some of these scattered objects then struck, or "bombarded," the planets and moons of the inner solar system.

This model, while radical, is compelling because it can explain many fundamental characteristics of the solar system, from the unusual orbits of the giant planets to the formation of several individual asteroid and comet populations. It also explains why the Moon experienced a barrage of impactors nearly 4 billion years ago. Thus the Moon, and its entire impact history, can be viewed as a "Rosetta Stone" for deciphering the histories of the planets.



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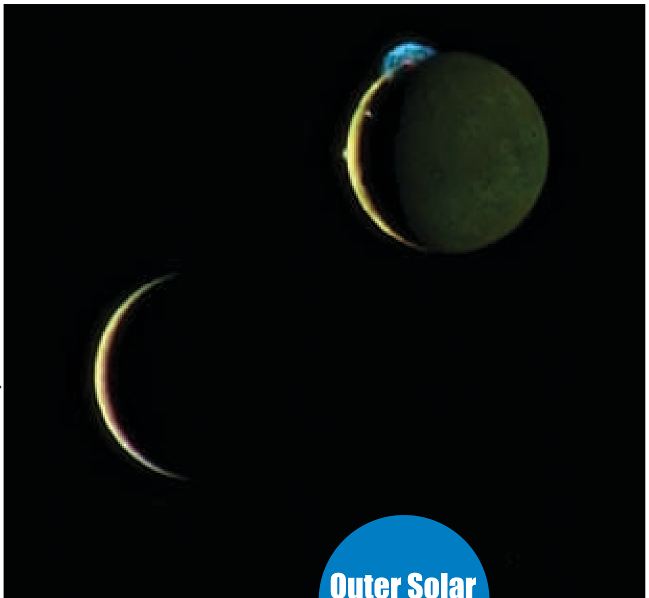
These frames simulate the first 1.2 billion years of solar system history. The orbits of the four giant planets are shown as colored ellipses. The green dots show small comet-like objects. Changes in the orbits of the giant planets cause the smaller objects to scatter widely, some of which strike the inner planets and moons in a "late heavy bombardment."



Courtesy NASA/JHU APL/SwRI D017278

The New Horizons spacecraft captured this image of Jupiter's moons Io (right) and Europa as it passed the giant gas planet in 2007. Three plumes from active volcanoes are visible on Io.

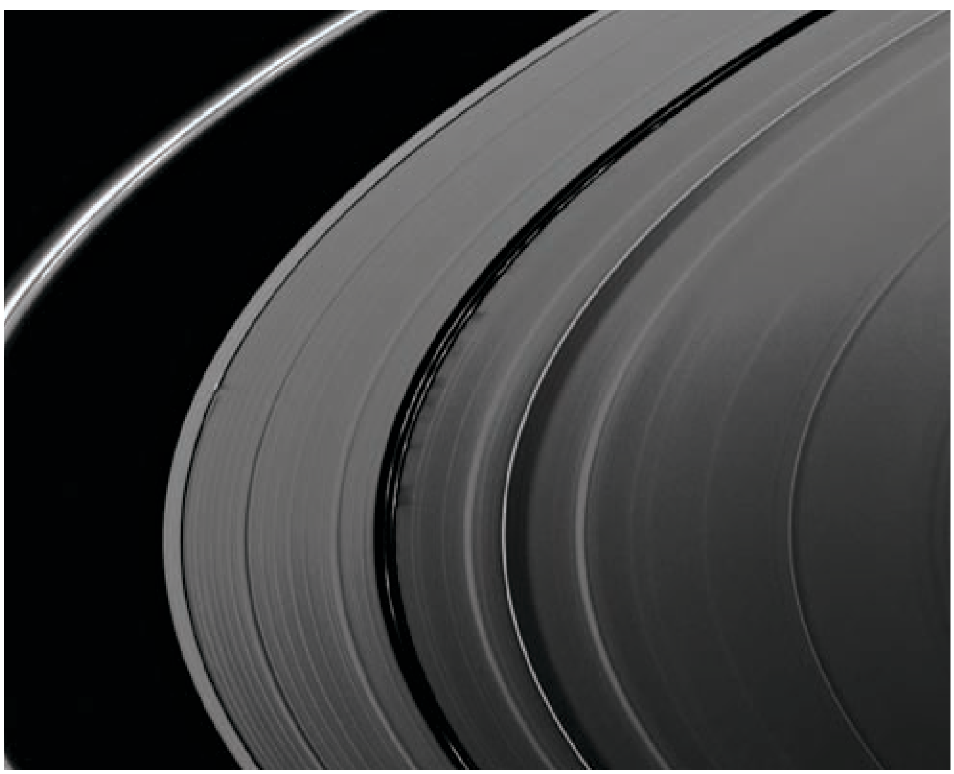
Outer Solar System

SwRI space science is active beyond the asteroid belt, in the realm of the giant planets and beyond. The New Horizons mission to Pluto was conceived at SwRI-Boulder and launched toward Pluto in January 2006. The spacecraft is now well beyond the orbit of Saturn, and will fly past Pluto and its moons Charon, Nix and Hydra (the last two co-discovered by Boulder staff) in July 2015, greatly improving our understanding of these worlds and icy dwarf planets in general.

New Horizons made its first discoveries in early 2007, when it flew past Jupiter at a range of 2 million km and used the giant planet's gravity to speed the journey to Pluto. The spacecraft's images of Jupiter itself revealed new details of its complex storm systems, including unprecedented near-infrared time-lapse views of ammonia-rich thunderstorms being torn apart by the planet's intense winds. New Horizons obtained some of the best-ever images of Jupiter's faint ring system, discovering a series of mysterious clumps of ring material. Images of its volcanic moon Io documented an enormous eruption from the volcano Tvashtar, obtaining movies of its 350-km-high plume. These close-up observations were supplemented using the Hubble Space Telescope and ground-based telescopes. The peculiar lumpy atmosphere of Io and charged particles that escape Io and fill the Jovian magnetosphere are subjects of additional ground-based and spacecraft investigations.

Even as it awaits the New Horizons flyby, Pluto is under regular scrutiny from Earth. Pluto's atmosphere was discovered in 1988 by means of stellar occultation, in which a planetary body passes between the observer and a background star. A subsequent pair of occultations in 2002 revealed, surprisingly, that the atmospheric pressure had doubled despite Pluto's increasing distance from the Sun. To further study these changes, the Boulder staff formed an occultation group in 2002, with members who have since traveled the world — wherever a star happens to cast Pluto's shadow on the Earth — to record five subsequent Pluto occultations using a combination of local observatories and portable telescopes. These data are detailing changes in the structure, dynamics and shape of Pluto's atmosphere, paving the way for New Horizons' 2015 close-up view.

Somewhat closer to home, NASA's Cassini spacecraft has been orbiting the ringed planet Saturn since 2004, providing unprecedented information about the planet and its moons. Staff members have been involved both in planning Cassini's observations and in understanding many facets of the data. In July 2005, Cassini's Composite Infrared Spectrometer (CIRS) revealed enormous amounts of thermal radiation from tectonic fractures at the south pole of Saturn's small moon Enceladus — one of a series of observations by multiple Cassini instruments that revealed Enceladus to be only the third world in the solar system, after Earth and Jupiter's Io, known to be currently volcanically active. The high heat flux and geological



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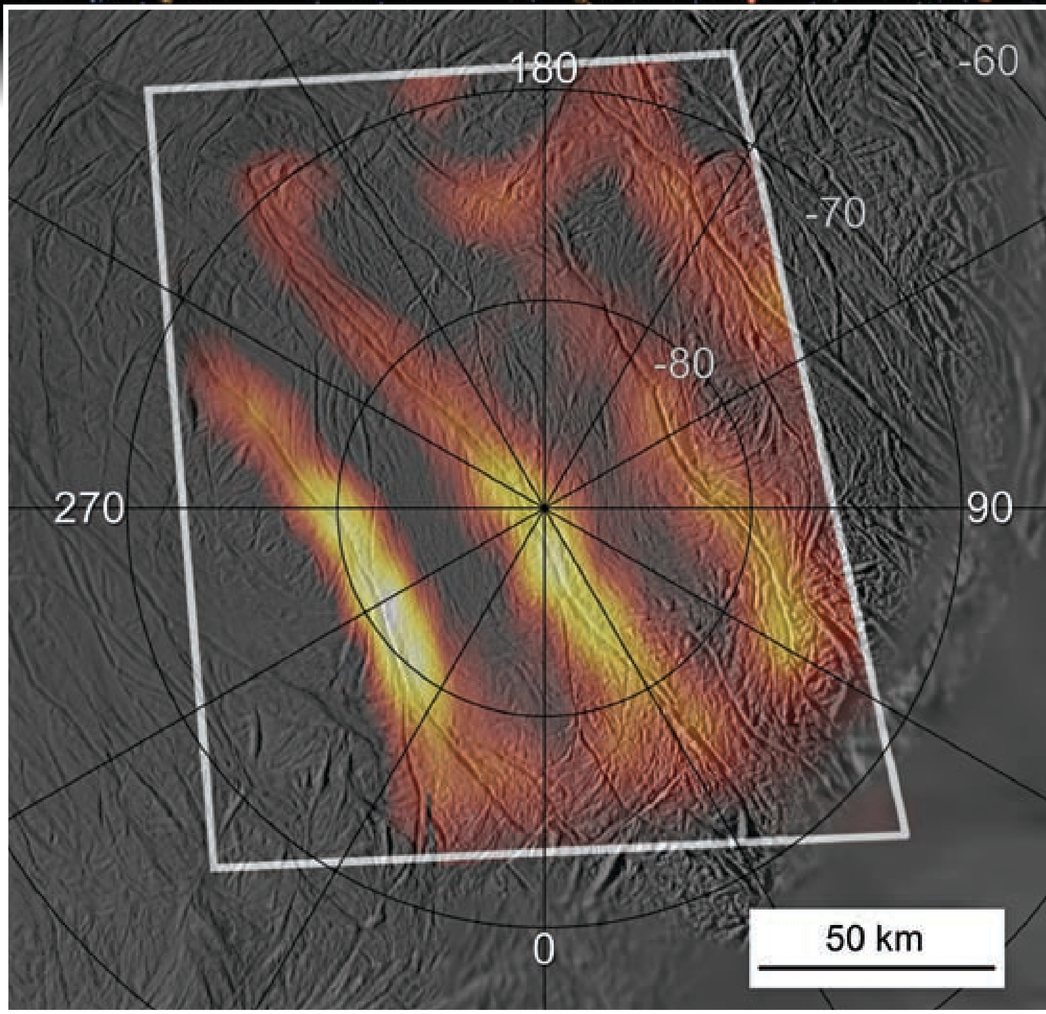
Courtesy NASA/JPL/SSI

Saturn's narrow F ring and broad A ring were photographed by the Cassini spacecraft soon after Saturn's August 2009 equinox. Shadows are cast onto the rings by thick clumps within or at the edges of empty gaps in the A ring.

activity near the moon's south pole is driven by tidal flexing of Enceladus due to its eccentric orbit around Saturn. Follow-on theoretical work suggests that Enceladus has an ocean beneath its ice shell. Energy created by tidally driven raising and lowering of the ice shell by tens of meters each day is transported to the surface by solid-state convection, which provides a natural explanation for the intense heat, volcanism and deformation.

Most exotic of all Saturn's moons is Titan. By far the largest moon, wrapped in a smoggy atmosphere almost five times as dense as Earth's, Titan also exhibits many of the same weather phenomena as Earth. The air is mostly nitrogen, similar to Earth's atmosphere, but the predominant volatile compound is methane, not water. Titan conditions permit methane to condense as both ice and liquid, so methane likely participates in a cycle similar to Earth's hydrological cycle. Atmospheric simulations indicate that a critical level of methane is required to initiate convective clouds. The relatively clear region where the Huygens probe landed in 2005 was far below this threshold. These clouds, which appear to be similar to terrestrial thunderstorms, can also produce centimeters to hundreds of centimeters of precipitation in only a few hours — sufficient to carve the river-like channel features observed across much of Titan's surface.



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Courtesy NASA/JPL/GSFC/SwRI/SSI

The active "tiger stripe" fractures at the south pole of Enceladus glow with internal heat in this composite, false-color image from the Saturn-orbiting Cassini spacecraft.

Like Earth, Saturn has seasons. During the first five years of Cassini's mission, Saturn's southern hemisphere experienced summer. In August 2009, the Sun crossed to the northern hemisphere and briefly illuminated Saturn's rings edge-on. During this event, which occurs just once every 15 years, the rings and moons cast shadows on each other. Most parts of the rings are only about 10 meters thick, due to the energy lost during collisions between ring particles. However, observations of the rings planned by SwRI Cassini scientists and colleagues during this year's "equinox" have shown that some parts of the rings are not meters, but several kilometers, thick.

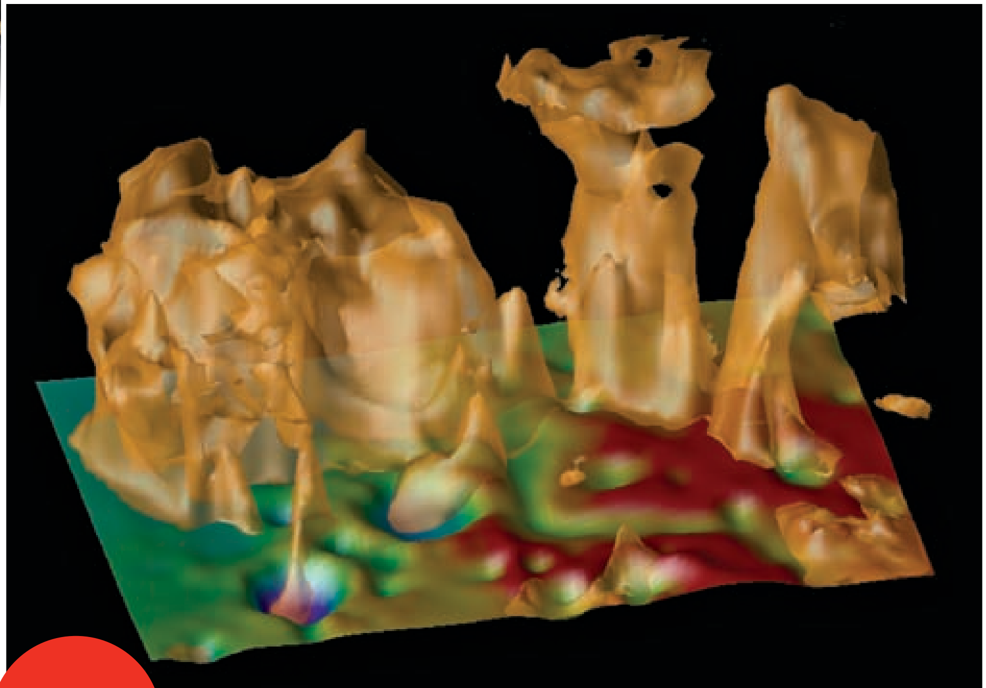
Space Science and Engineering

Research at the Planetary Science Directorate complements and extends the significant space research program long operated at SwRI's headquarters in San Antonio. The Space Science and Engineering Division comprises more than 370 employees in Boulder and San Antonio focused on spacecraft instrument development, as well as observational and theoretical space and planetary science.

SwRI currently serves as the principal investigator institution for NASA's Interstellar Boundary Explorer (IBEX) Small Explorer mission and the New Horizons and Juno New Frontiers missions. In addition, SwRI leads the science investigation for NASA's four-spacecraft Magnetospheric Multiscale mission.

Staff members in Boulder and San Antonio routinely share their expertise with the national and international media and have appeared in television documentaries. Researchers also have published books and articles and provided expert opinion before the U.S. Congress on such issues as asteroid impact hazards to Earth.

Funding from the National Aeronautics and Space Administration, the National Science Foundation, SwRI's internal research program and other sources supports this array of space research activities through competitively selected proposals. Research results are published in a variety of professional, peer-reviewed journals.



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Towering dust storms over 15 km in height bear down on one of the proposed Mars Science Laboratory (MSL) landing sites, Mawrth Valles, as simulated by the Mars Regional Atmospheric Modeling System (MRAMS). The atmospheric information provided by the model is being used to establish the safety of proposed MSL landing sites and to guide descent and landing operations.

Mars

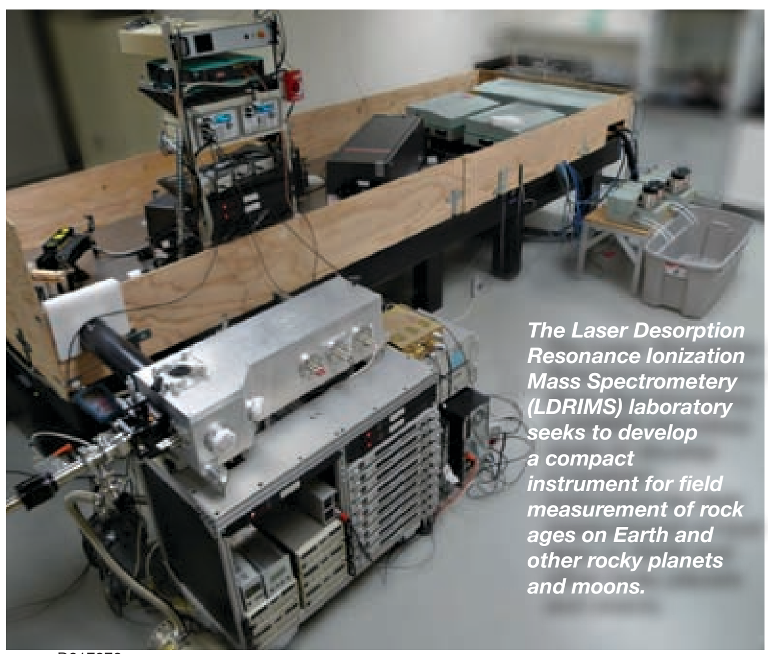
Studies of Mars span the planet's atmosphere, surface and interior, both past and present. Atmospheric modeling of Mars is important both for basic science and for weather forecasts critical to the successful landing and operation of spacecraft on the Martian surface. Following recent successes with predictions for the landings of the Mars Exploration Rover and Phoenix spacecraft, SwRI scientists are providing similar forecasts for the Mars Science Laboratory, a large rover scheduled to land in 2012. MSL uses a new landing system that hovers above the surface and lowers the rover on a cable. The system is sensitive to density perturbations and winds, for which observations are lacking or completely absent but which can be assessed with models that already have an excellent track record of accurate predictions.

Atmospheric modeling is illuminating the physics of Mars' famous dust storms. Large storms may generate electrical fields strong enough to trigger lightning, but even dust devils may produce electric fields strong enough to dissociate carbon dioxide and produce superoxides. These oxidizing molecules could be produced in high enough concentration to sterilize the surface of Mars and to rapidly destroy methane. This may help constrain whether methane is produced by biological or geochemical processes.

The thermal infrared spectra of geological materials are measured in two laboratories, where SwRI scientists are helping to develop spectral libraries of phases important to the interpretation of remote-sensing data of planetary surfaces, such as the mapping of igneous, aqueous, and weathering-derived phases on Mars and small bodies. For example, through global-scale mapping of the igneous mineral olivine, the team inferred a broader evolution of magma compositions over time on Mars than had been previously recognized. Laboratory simulations of water-rock interactions on Mars track the evolution of the near-surface environment and suggest that magnesium sulfate salts are dominant under acidic conditions that likely are representative of early Mars. Such salts were found by NASA's Mars Exploration Rover Opportunity. Alkaline conditions, thought to have prevailed through most of Mars' history, produce mostly calcium sulfates in the laboratory.

Scientists also are working to understand the effects of small particle sizes and vacuum environments on infrared spectra, which will aid in the identification and numerical abundance modeling of phases on airless bodies with powdery surfaces, such as asteroids and the Moon.

Below the microwave band, electromagnetic energy penetrates into the interiors of rocky and icy bodies. Signals from the Shallow Radar (SHARAD) instrument onboard NASA's Mars Reconnaissance Orbiter were able to penetrate a 3-km-thick stack of layers in the planet's north polar region. Staff analysis of those signals revealed a cyclical pattern of strongly reflective, layered materials, interleaved with zones of lower reflectivity. These patterns track models of Martian climate cycles for the past four million years and constrain the age, composition and atmospheric precipitation of the ice-rich layers.



The Laser Desorption Resonance Ionization Mass Spectrometery (LDRIMS) laboratory seeks to develop a compact instrument for field measurement of rock ages on Earth and other rocky planets and moons.

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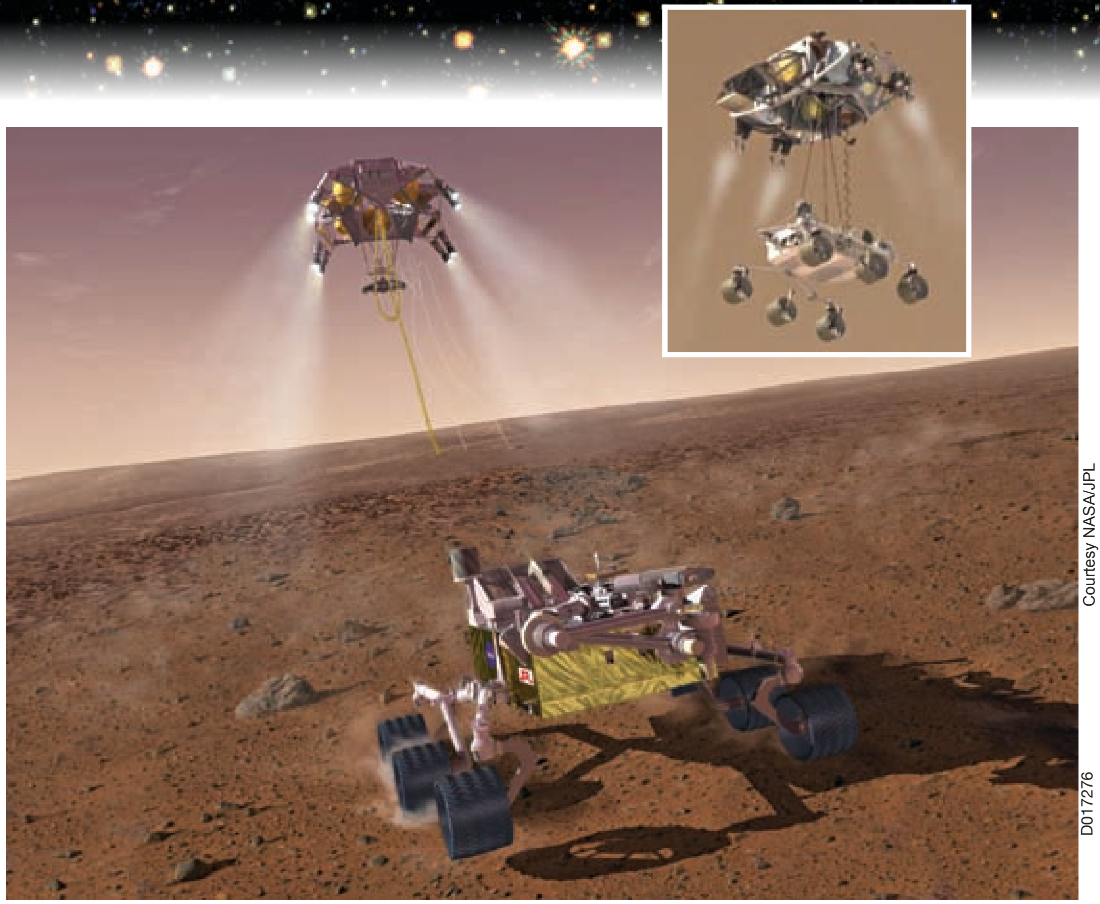
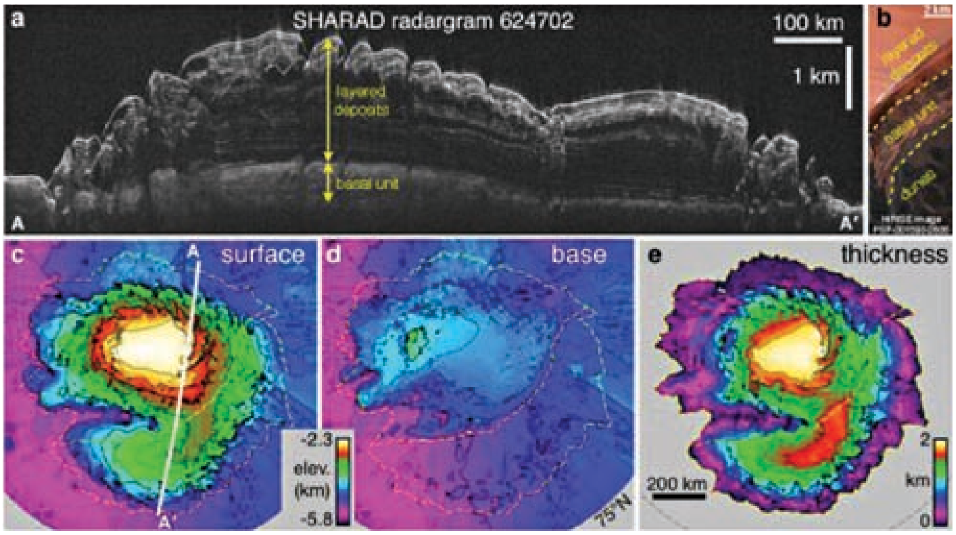
Below even radar frequencies lies a vast underworld of the electromagnetic spectrum where energy is transported by diffusion instead of as waves. Because this energy can penetrate solid rock to depths of hundreds of kilometers, it is useful for probing the structure, temperature and composition of the interiors of solid planets and moons. Staff members are extending the limits of terrestrial geophysics and performing laboratory measurements to enable this next advance in planetary subsurface exploration. Byproducts of this work include new knowledge of the structural chemistry of ice, soil-ice electrical interactions, and attribution of broadband dispersion and loss in surface-penetrating radar — both on Earth and on Mars — to thin films of adsorbed water.

In contrast to the relatively small quantities of water concentrated in the polar caps and dispersed in the crust today, it has long been thought that large quantities of discharged groundwater must have shaped the early Martian surface. Adapting terrestrial hydrogeological models to Mars, SwRI scientists found that the discharged groundwater was most likely supplied by recharge on the nearby Tharsis rise, but that such connections were regional, and not global, in scale. Large lakes were intermediate reservoirs for groundwater discharge. These interactions represent a true hydrologic cycle on early Mars.

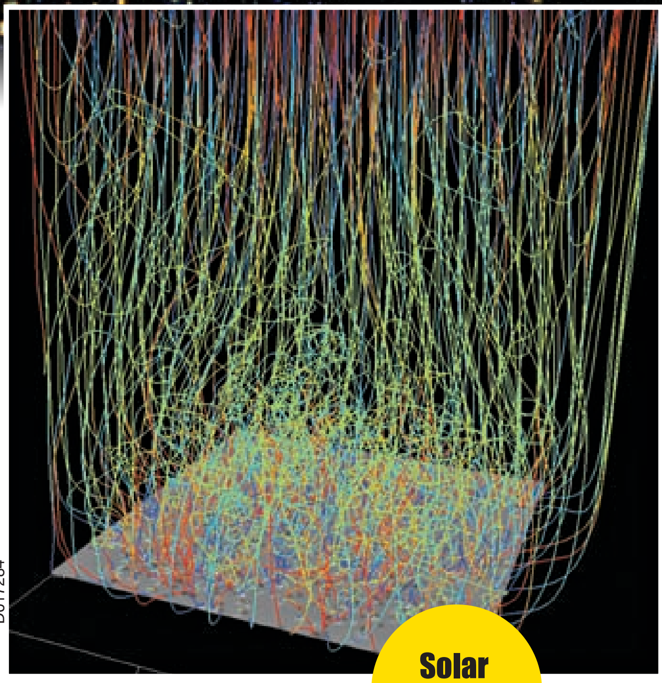


This artist's rendition of the Mars Science Laboratory (MSL) landing on Mars in 2012 illustrates the new "Sky Crane" system. SwRI's Radiation Assessment Detector (RAD) is onboard.

Determining the age of a rocky surface is one of the pivotal measurements that can be made in planetary geology, yet this has been done only for samples returned by astronauts from the Moon. SwRI has a major effort under way to develop a portable Laser Desorption Resonance Ionization Mass Spectrometer (LDRIMS), a backpack-size instrument that can determine rock ages from a robotic lander or a rover. LDRIMS uses the classic method of measuring the radioactive decay of rubidium and strontium. The current benchtop prototype can measure standards with 10 parts per million net strontium to ±0.5 percent, and one-part-per-10-billion sensitivity, in less than one minute. Models of the error in the age measurement, assuming the composition of meteorites known to have come from Mars, show that dates accurate to 50 million years are possible in a few hours.



This cross-section of the north polar cap of Mars (a) produced by ice-penetrating radar shows internal layering, likely due to layers of dust and ice (b). Composite images of many spacecraft passes allow a map of ice thickness to be developed (c–e).



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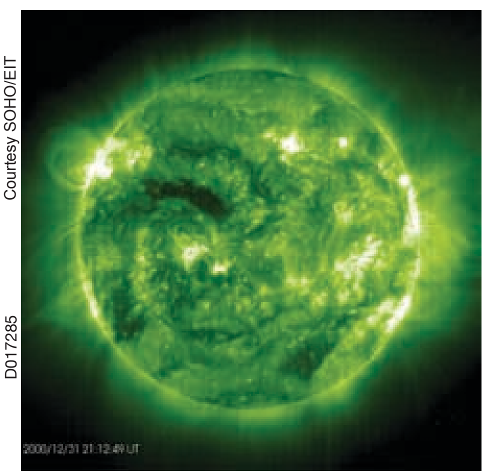
Magnetic field lines entwine and tangle in this fluxon simulation of a small (30,000 miles square) piece of the Sun's atmosphere.

Solar Physics

Current work in solar physics focuses on understanding how the Sun produces its magnetic field, and how ongoing changes in the surface magnetic field give rise to space weather and related effects throughout the solar system.

Staff members have developed computer vision software to identify and track hundreds of thousands of magnetic features on the surface of the Sun simultaneously, determining their motion and history as they interact with one another. In this way, the nature of the Sun's complex magnetic dynamo can be probed. By statistically analyzing the history of magnetic features, the team demonstrated that the solar magnetic field is dominated by dynamo action on scales no larger than 100 miles. The computer vision software is currently being deployed as part of the data pipeline for NASA's Solar Dynamics Observatory. In addition to relating magnetic activity to features in the solar corona, it will be used to identify new emerging flux regions on the Sun and predict space weather in real time.



D017285 Courtesy SOHO/EIT

Magnetic loops and structures are visible in this ultraviolet image of the Sun's corona.

Magnetic field lines in the electrically conductive plasma of the Sun can become stretched, twisted and tangled. When field lines suddenly snap and reconnect, plasma can be hurled out as a solar flare or a larger coronal mass ejection (CME). The new "fluxon" simulation of the solar magnetic field treats field lines directly as physical objects, rather than as a distributed field in space, as has been the traditional approach. The high fidelity at a hundred-fold increase in computation speed has been remarkable. This enabled scientists to identify a new type of instability that causes magnetic explosions without reconnecting field lines.

Understanding dynamics and magnetic field evolution on the Sun requires new instruments that can extract information from the solar spectrum quickly and at high spatial resolution. The Planetary Science Directorate has a strong solar instrument development program. Two prototype instruments — SHAZAM and RAISE — take quite different approaches to measuring the solar spectrum. RAISE is an ultraviolet imaging spectrograph that is undergoing final testing before launch in the spring of 2010. It will collect several spectra per second, accumulating some 27,000 in all, during a single six-minute suborbital rocket flight. SHAZAM is a high-speed Doppler magnetograph that uses a new measurement technique — spectral stereoscopy — to measure the smallest magnetic features on the Sun using subtle polarization effects in sunlight. SHAZAM will ultimately be deployed on the world's largest solar telescope, the 4-meter Advanced Technology Solar Telescope under construction on the Hawaiian island of Maui.

The solar group will continue to study solar roots of space weather phenomena, predicting and tracking CMEs from spacecraft and ground-based radiotelescopes. Further spectral imager and flight-instrument development is facilitated by a new heliostat lab. The RAISE sounding rocket has provided a gateway into major instrument projects, including the new SPICE UV imaging spectrograph that has been selected to fly to the inner solar system on board the European Solar Orbiter mission in 2017.

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The SHAZAM instrument was recently deployed at the National Solar Observatory facility near Alamogordo, N.M. The telescope is more than 300 feet tall, with two-thirds of it underground.

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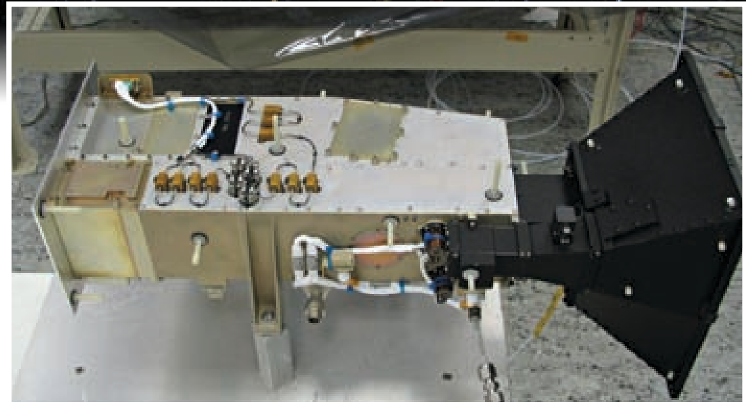
Europa rises past the limb of Jupiter as seen by the New Horizons spacecraft.



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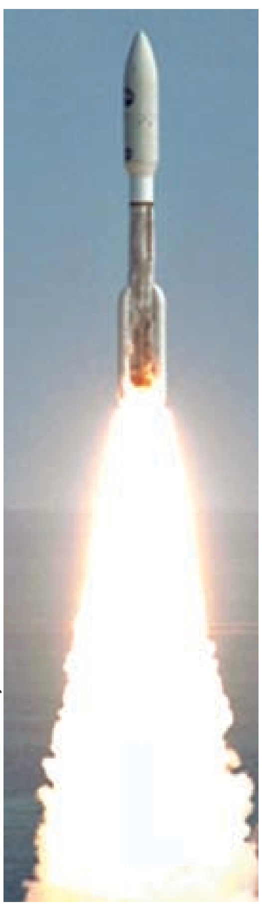
The Lyman Alpha Mapping Project (LAMP) instrument is currently operating on the Lunar Reconnaissance Orbiter to produce maps of the Moon's surface, water absorption features and tenuous atmosphere.

Space Operations

Complementing the innovative research at SwRI-Boulder is the Science Operations Center, which supports a growing number of robotic missions. The SOC performs three main tasks: designing the commands that control the capture of images and data by spacecraft, automated processing of data returned to Earth and archiving data for generations to come.

The most active and prominent current mission is the New Horizons mission. Now past Saturn's orbit on its way to Pluto, the spacecraft is entering hibernation, but planning activity is still going strong. The SOC acts partly as an interface between the science team (where specific mission observations are carefully selected) and the Mission Operations Center at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md., which sends commands to the spacecraft. While New Horizons peacefully drifts toward the outer reaches of our solar system, the SOC's uplink sequencing team is developing commands for the complex maneuvers that will take place during the Pluto encounter in 2015.



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Courtesy NASA

The fastest spacecraft ever launched, New Horizons lifts off from Cape Canaveral Jan. 19, 2006, on its nine-year journey to Pluto.

Three UV spectrometers on active missions are supported at the SOC. The ALICE instruments onboard New Horizons and Rosetta will examine the surfaces and tenuous atmospheres of Pluto and the comet Churyumov-Gerasimenko, respectively. The LAMP instrument, currently orbiting the Moon on the Lunar Reconnaissance Orbiter, seeks to peer into permanent shadows near the poles and identify frosts. The SOC also performs data processing for the Mars Reconnaissance Orbiter's SHARAD instrument, and its scientists and engineers are designing data pipelines for RAISE and SHAZAM. Science operations for MSL's Radiation Assessment Detector will be executed at the SOC. The growing experience base makes the SOC a valuable resource for future spaceflight projects. ❖

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For more information about the Planetary Science Directorate and its programs, contact (303) 546-9670 or boulder@swri.org.