In the 1930s, Conrad and Marcel Schlumberger began development of tools and sensors to explore Earth’s inner space. Some 75 years later, similar detectors are helping scientists investigate the fundamental nature and origin of objects in outer space.

On a cold day in February 2001, a spacecraft landed on 433 Eros, an asteroid between the orbits of Mars and Jupiter. The spacecraft had completed its five-year journey to investigate fundamental questions about the nature and origin of near-Earth objects for the first time.

The technical demands of the Near Earth Asteroid Rendezvous NEAR-Shoemaker (NEAR) mission were immense. A multidisciplinary team of US National Aeronautics and Space Administration (NASA) scientists and engineers drew from many scientific and industrial resources, including the predominantly inner-Earth-focused oil and gas industry.

Applying technologies developed for oil and gas exploration to scientific endeavors is not a new practice. Oilfield technologies have often been applied in the interest of science. For example, deep-drilling projects conducted on land and in most major oceans of the world have contributed to our understanding of Earth’s past as well as its future.

Engineers and scientists with the internationally funded Ocean Drilling Program began subsea drilling operations in 1961 to explore the hard outer layer of the Earth’s crust, or lithosphere. Scientists used tools and techniques developed for oil and gas exploration to document continental drift and to generate a substantial quantity of data relating to plate tectonics.1

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4. Acceleration is often expressed in units of g-force (g_n), which is defined as 9.80665 m/s², approximately equal to the acceleration due to gravity on the Earth’s surface at sea level.
In 2004, engineers drilling in the Arctic Ocean at the crest of the Lomonosov ridge provided preliminary evidence that the Arctic was ice-free and warm about 56 million years ago. Scientists analyzed cores recovered from the drilling project to help determine when, why and how the Arctic temperature changed. They also gained insight into current global-warming trends.

Understanding the fundamental processes that occur deep within the Earth’s crust has contributed to our knowledge of many inner-earth events, including volcanic activity, plate tectonics, weather fluctuations, and chemical and thermodynamic processes that lead to mineral deposition.

Hydrocarbons are most often found in forbidding environments. Tools and sensors are stressed to their limits as boreholes are drilled deeper into the Earth’s crust where high temperature and pressure and excessive vibrations are common, and stress and shock forces reach thousands of times the acceleration of gravity ($g_n$). Tools and instruments must also survive extreme thermal cycles, from the cold surface of the Arctic to temperatures higher than 204°C [400°F] in the downhole environment. Drilling, logging and measurement instruments have evolved to meet these challenges. Today, oil and gas E&P tools and instruments are designed and thoroughly tested for extended exposure to these harsh environments.

Similarly, the forces encountered while launching and accelerating a vehicle into space can be traumatic to equipment components. For example, the shock of pyrotechnic-stage separation can reach over 4,000 $g_n$, stressing both the vehicle and its payload. Once in space, depending on orientation relative to the Sun, temperature extremes range from more than 100°C [212°F] to below -200°C [-328°F]. Because of the need to operate in harsh environments, the tools and instrument packages designed for deep-well drilling are inherently applicable to other challenging environments, such as outer space.

Whether exploring inner space for scientific purposes, searching for oil and gas or probing the vastness of outer space, the desire to explore has driven the history of modern civilizations. This drive led, at least in part, to the conquest of the moon in the 1960s, marking the beginning of a new generation in space exploration and travel. More recently, spacecraft, such as the Hubble Space Telescope (HST), aided by technologies developed for oil and gas exploration, have peered from Earth orbit ever more sharply and deeply into the universe beyond our solar system (previous page).
As we move from exploration of inner space to that of outer space, the tools and techniques developed for exploration deep beneath the Earth's surface are helping to uncover the mysteries of our solar system and the far reaches of space. In this article, we discuss a few of the recent contributions made to space exploration by the scientists and engineers of the petroleum industry. Although the mission of the NEAR spacecraft has ended, oilfield technology aboard the HST and the Cassini-Huygens Saturn probe continues to expand our knowledge and chart our way forward in the quest for knowledge.

**Keeping the Hubble on Target**

Throughout history, our understanding of the universe has been limited by what we could see. The invention of the telescope enhanced our vision and allowed observations by Copernicus, Kepler and Galileo in the 16th and 17th centuries to show that the Earth was not the center of the universe. By the 18th century, the development of the telescope helped scientists investigate the cosmos. Increasingly bigger and better telescopes have routinely discovered and documented planets, stars and nebulae that are invisible to the naked eye.

As recently as the beginning of the 20th century, most astronomers still believed that the universe consisted of a single galaxy, the Milky Way—a collection of stars, dust and gas in the vastness of space. However, the universe as we knew it changed in 1924 when American astronomer Edwin Hubble used the 2.54-m [100-in.] Hooker Telescope on Mount Wilson, near Los Angeles, to observe billions of other galaxies beyond the Milky Way.

For astronomers like Edwin Hubble, there has always been a major obstacle to a clear view of the universe—the Earth's atmosphere. Gases and airborne particulates in the atmosphere blur visible light, cause starlight to scintillate, or twinkle, and hinder or totally absorb infrared, ultraviolet, gamma ray and X-ray wavelengths.

To minimize atmospheric distortion, scientists built observatories on mountaintops and away from the areas of highly radiated light, or sky glow, found near large cities. This effort met with varying levels of success. Today, adaptive optics and other image-processing techniques have minimized, but not totally eliminated, atmospheric effects.

In 1946, Princeton astrophysicist Lyman Spitzer documented the potential benefits of a telescope in space, well above Earth's atmosphere. Then, following the launch of the Soviet satellite Sputnik in 1957, NASA placed two orbital astronomical observatories (OAO) into Earth orbit. The OAOs made a number of ultraviolet observations and established the basic principles for the design, manufacture and launch of future space observatories.

Scientific, governmental and industrial groups continued the move toward extraterrestrial exploration by planning the next step beyond the OAO program. Spitzer gathered the support of other astronomers for a large orbital telescope, later called the Hubble Space Telescope, and in 1969, the National Academy of Sciences approved the project.

NASA's Goddard Space Flight Center in Greenbelt, Maryland, USA, was responsible for scientific instrument design and ground control for the space observatory. In 1983, the Space Telescope Science Institute (STScI) was established at The Johns Hopkins University in Baltimore, Maryland. The staff of STScI managed the telescope's observation time and data. NASA chose the Marshall Space Flight Center in Huntsville, Alabama, USA, as the lead NASA field center for the design, development and construction of the space telescope. Perkin-Elmer Corporation, now Hughes Danbury Optical Systems, developed the optical telescope assembly and the fine-guidance sensor (FGS) system.

On April 24, 1990, after numerous project delays, the space shuttle Discovery lifted off from Earth carrying the HST in its cargo bay. The following day, the school-bus-size space telescope was deployed in low-Earth orbit (above left). Free of atmospheric distortion, the giant telescope mirror began its mission of gathering photons from as far away as the edge of the known universe.
Critical to the performance of the HST is staying on target for extended periods of time. Electromagnetic waves emitted from distant objects are often faint or weak, so the HST must stay perfectly positioned while the photons are being collected in sufficient quantities to form an image. To accomplish this, engineers used the Schlumberger oilfield photomultiplier-tube technology to design the FGS system.  

An FGS is essentially a targeting camera capable of making celestial measurements, locking onto guide stars and providing data for maneuvering the telescope. Two FGSs are used to point the telescope at an astronomical target and hold that target in the telescope’s field of view; the third FGS can then be used for astrometry measurements.

The FGS system can maintain pointing accuracy to 0.007 arcseconds, allowing the telescope’s pointing-control system (PCS) to keep the Hubble telescope on target during camera exposure times of 10 hours or more. The PCS combines a number of different sensor subsystems to achieve this milliarcsecond pointing accuracy. This level of accuracy and precision is comparable to training a laser beam on a target the size of a thumbnail from a distance of 442 km [275 miles].

Within the housing of each FGS instrument are two orthogonal white-light, shearing interferometers, their associated optical and mechanical elements and four Schlumberger S-20 photomultiplier tubes (PMTs) (above right). These PMTs are based on the same rugged construction as those used in well-logging instruments. The photocathode was manufactured using the same technology as tubes used in oilfield service applications. For use on the HST, the PMTs were designed to be sensitive over a spectral range of 400 to 700 nanometers (nm), with an efficiency of approximately 18% at the blue end of the electromagnetic spectrum and diminishing linearly to about 2% at the red end.

Each FGS interferometer consists of a polarizing beam splitter followed by two Koesters prisms. To measure the direction of the light emitted by a guide star, the pairs of Koesters prisms are oriented perpendicular to one another. The angle of the wavefront in the X and Y planes gives the precise angular orientation of the guide star relative to the Hubble’s optical path. These data, once fed into the PCS, are used to control the telescope orientation relative to a guide star.

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**References:**

7. Adaptive optics is a technology used to improve the performance of optical systems by reducing the effects of rapidly changing optical distortion typically resulting from changes in atmospheric conditions. Adaptive optics works by measuring the distortion and rapidly compensating for it using either deformable mirrors or material with variable refractive properties.
12. Astrometry is a branch of astronomy that deals with the positions of stars and other celestial bodies, their distances and movements.
13. A second of arc, or arcsecond, is a unit of angular measurement that comprises one-sixtieth of an arcminute, or \( \frac{\pi}{3600} \) of a circle. It is the angular diameter of an object of 1 unit diameter at a distance of \( 360x60x60/(2\pi) \approx 206,265 \) units, such as (approximately) 1 cm at 2.1 km.
14. Interferometers were first used by Michaelson, who won the Nobel Prize in 1907 for his work using an optical interferometer to accurately measure the speed of light.
In addition to guiding the HST, the accuracy of FGS sensors makes them useful for high-precision astrometric measurements. These measurements help scientists determine the precise positions and motions of stars. The FGS sensors can provide star positions about 10 times more precisely than measurements made with ground-based telescopes. Scientists use astrometric measurements to help define wobble in the motion of stars that might indicate the presence of a planetary companion (below left). The motions of stars can also determine whether a star pair represents a true binary star system, or simply an optical binary.15

Aided by elements of oilfield technology, the Hubble Space Telescope continues its work today. Scientists are using instruments like the HST to search the far reaches of the universe and uncover secrets of the past while reaching into our future.

Asteroids—Up Close and Personal
A little closer to home, technologies developed for oilfield use are helping scientists explore asteroids in our solar system. These large pieces of rock are primordial objects left over from the formation of the solar system. Some scientists have suggested that asteroids are the remains of a protoplanet that was destroyed in a massive collision. However, the prevailing view is that asteroids are leftover rocky matter that never successfully coalesced into planets.

Scientists theorize that the planets of the solar system formed from a nebula of gas and dust that coalesced into a disk of dust grains around the developing Sun. Within the disk, tiny dust grains coagulated into larger and larger bodies called planetesimals, many of which eventually accreted into planets over a period of 100 million years. However, beyond the orbit of Mars, gravitational interference from Jupiter prevented protoplanetary bodies from growing to diameters larger than about 1,000 km [620 miles].16

Most asteroids are concentrated in an orbital belt between Mars and Jupiter (below). These space rocks orbit the Sun as planets do, but they have no atmosphere and very little gravity. The asteroids in the belt comprise a significant fraction of the solar system’s solid matter that has not yet coalesced into planets.

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amount of material—putting all of the asteroids together would form a body about 1,500 km [930 miles] in diameter, roughly half the size of Earth's moon.\(^7\)

Not all asteroids are far away in the asteroid belt. Some, called near-Earth asteroids (NEAs), have orbits that bring them close to Earth. Astronomers believe NEAs to be fragments ejected from the main asteroid belt by asteroid-asteroid collisions or by gravitational perturbations from Jupiter. Some NEAs could also be the nuclei of dead, short-period comets.

Since many asteroids have historically struck Earth and its moon, understanding their composition and origin may be a key to our past as well as our future. Scientists believe that the chemical building blocks of life and much of Earth's water may have arrived on asteroids or comets that bombarded the planet in the early stages of its development (above left). One widely accepted theory suggests that an asteroid measuring at least 10 km [6 miles] across, impacted the Earth some 65 million years ago, causing mass extinctions among many life forms, including the dinosaurs.

Astronomers suspect that the approximately 800 NEAs found to date represent only a small percentage of their total population. The largest presently known is 1036 Ganymede, with an approximate diameter of 41 km [25.5 miles]. NEAs with diameters greater than 1 km [0.6 miles] are known as potentially hazardous asteroids, suggesting that should they strike Earth, they could threaten life as we know it.

Of the more than 700 known potentially hazardous asteroids, one of the largest is Toutatis, an asteroid that is nearly 1.6 km [1 mile] long and orbits around the Sun within one-half degree of Earth's orbital plane. In December 1992, Toutatis passed within 0.024 astronomical units (AU), or 9.4 lunar distances from Earth.\(^6\) Then, on September 29, 2004, Toutatis's orbital path brought it within 0.01 AU of Earth—the closest approach of any large asteroid in the 20th century.

Although astronomers have known about asteroids for nearly 200 years, until recently, their basic properties, their relationship to meteorites found on Earth and their origins remained a mystery. NASA and the scientific community, driven by both the desire to understand asteroids and the threat to Earth presented by NEAs more than 1 km in diameter, set in motion the plans for the NEAR project.

### A Mission of Many Firsts

In 1990, NASA introduced a new program of planetary missions called the Discovery program. By 1991, the first mission was chosen—a rendezvous with near-Earth asteroid 433 Eros. The Johns Hopkins University Applied Physics Laboratory (JHUAPL) was chosen to manage the project, and in 1995, the NEAR spacecraft was shipped to the Kennedy Space Center in Florida.\(^5\)


The NEAR spacecraft was renamed NEAR–Shoemaker to honor planetary geologist Eugene Shoemaker (1928–1997).

15. The term binary star refers to a double-star system, or a union of two stars into one system based on the laws of attraction. Any two closely spaced stars might appear from Earth to be a double-star pair when, in fact, they are a foreground and background star pair widely separated in space. These systems are typically referred to as optical binaries.


17. NASA, reference 16.


19. The NEAR spacecraft was renamed NEAR–Shoemaker to honor planetary geologist Eugene Shoemaker (1928–1997).

The large S-type potato-shaped asteroid is one of the most elongated asteroids. It orbits around the Sun, rotating on its axis once every 5.27 hours, with a perihelion of 1.13 AU and an aphelion of 1.78 AU (top).

NEAR departed Earth for asteroid Eros on February 17, 1996, riding on top of a Delta-II launch vehicle. One year later, on February 18, 1997, NEAR reached its most distant point from the Sun, 2.18 AU, setting a new distance record for a spacecraft with instrumentation powered by solar cells.

By the end of its five-year mission, NEAR would produce an impressive list of spacecraft firsts: the first spacecraft with instrumentation solely powered by solar cells to operate beyond the orbit of Mars, the first to encounter a C-type asteroid, the first to encounter a near-Earth asteroid, the first to orbit a small body, and the first spacecraft to land on a small body.

NEAR—The Scientific Mission

Prior to the NEAR mission, our knowledge of asteroids came primarily from three sources: Earth-based remote sensing, data from the Galileo mission flybys of the two main-belt S-type asteroids 951 Gaspra and 243 Ida, and laboratory analyses of meteorites recovered after impact with the Earth.

Although astronomers theorize that most meteors result from the collision of asteroids, they may not be completely representative of all materials that comprise NEAs. Clear links between meteorite types and asteroid types proved difficult to establish.

Some S-type asteroids appear to be fragments of bodies that underwent substantial melting and differentiation, while others consist of what appears to be nonmelted primitive materials like chondrites. Scientists believe that nonmelted S-type asteroids may have preserved the characteristics of the solid material from which the inner planets accreted.

The Galileo mission flybys provided the first high-resolution images of asteroids in the early 1990s. Images revealed complex surfaces covered by craters, fractures, grooves and subtle color variations (left). However, Galileo’s instrumentation was not capable of measuring elemental composition, so prior to the NEAR mission, scientists continued to be unsure of the relationship between ordinary chondrites and S-type asteroids.

Mission engineers believed that the NEAR data, when combined with those from the Galileo flybys, would help scientists understand the relationship between S-type asteroids and other small bodies of the solar system. The NEAR mission’s primary objectives were to rendezvous with, achieve orbit around and conduct the first scientific exploration of a near-Earth asteroid.

The NEAR Spacecraft

Engineers designed NEAR’s systems to be solar-powered, simple and highly redundant. Onboard NEAR were five instruments designed to make detailed scientific observations of the gross physical properties, surface composition and morphology of Eros. These five were the multispectral imager (MSI), near-infrared spectrometer (NIS), magnetometer (MAG), NEAR laser rangefinder (NLR) and the combined X-ray, gamma ray spectrometer (XGRS) (next page).

The MSI imaged the surface morphology of Eros with spatial resolutions down to 5 m [16.4 ft], while scientists used the NIS to measure mineral abundances at a spatial

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The MSI imaged the surface morphology of Eros with spatial resolutions down to 5 m [16.4 ft], while scientists used the NIS to measure mineral abundances at a spatial
resolution on the order of 300 m [984 ft]. The MAG was used to define and map intrinsic magnetic fields on Eros.

Scientists used the NLR to enhance the surface morphology profiles derived from NEAR’s imaging camera. The NLR is a laser altimeter that measures the distance from the spacecraft to the asteroid surface by sending out a short burst of laser light and then recording the time required for the signal to return from the asteroid. The ranging data were used to construct a global shape model and a global topographic map of Eros with a spatial resolution of about 5 m.

The XGRS was the primary tool used for surface and near-surface elemental analysis of Eros. Scientists combined data from the XGRS, MSI and the NIS to produce global maps of Eros’s surface composition.

Development of the complex XGRS system began about three years prior to launch. The instrument was designed to detect and analyze X-ray and gamma ray emissions from the asteroid surface from orbital altitudes of 35 to 100 km [22 to 62 miles]. Although spectroscopy of remote surfaces is possible during spacecraft flyby operations, measurements made while orbiting allow longer observation times and produce higher quality spectral data.

X-rays emitted from the Sun shining on Eros produce X-ray fluorescence from the elements contained in the top 1 mm [0.04 in.] of the asteroid’s surface. In the absence of any significant atmosphere that might otherwise absorb X-ray emissions, elements fluoresce at energy levels that are characteristic of specific elements. Scientists used the X-ray fluorescence energy detected in the 1- to 10-keV level to infer surface elemental composition.

The XRS subunit consists of three identical gas-filled proportional counters that provide a large active surface area and therefore the sensitivity required for remote sensing. Similar detectors have been used on lunar orbital missions and most recently on Apollo missions.

The X-ray gas tubes are not particularly sensitive to temperature change, since the multiplication effect depends more on the number of gas molecules than the gas pressure. However, the gain in the gas tubes is sensitive to voltage variations.

Gamma ray spectrometry provides a complementary measurement of near-surface elemental composition. The gamma ray spectrometer (GRS) detects discrete-line gamma ray emissions in the 0.1- to 10-MeV energy range.

At these energy levels, oxygen [O], silicon [Si], iron [Fe] and hydrogen [H] become excited, or radioactively activated, from the continual influx of cosmic rays. The GRS also detects naturally radioactive elements such as potassium [K], thorium [Th] and uranium [U]. The measurements have been used for years in oil and gas well logging to determine the physical and elemental composition of reservoir rock.

Unlike the low-energy X-rays, gamma rays are not as easily absorbed and therefore can escape from regions beneath the surface, allowing the GRS to reveal elemental composition to depths as much as 10 cm [4 in.] below the surface. By comparing elemental analysis from the XRS and GRS, scientists inferred the depth and extent of the dust layer, or regolith, covering the surface of Eros.26

21. Asteroids are classified based on reflectance spectrum and light-reflection characteristics, or albedo, which are indicators of surface composition. S-Type (silicaceous) asteroids are more prevalent in the inner part of the main asteroid belt, while C-Type (carbonaceous) asteroids are found in the middle and outer parts of the belt. Together, these two types account for about 90% of the asteroid population.

Perihelion and aphelion are the orbital points nearest and farthest from the center of attraction—in this case, the Sun.

22. A meteorite is a solid portion of a meteoroid that survives its fall to Earth. Meteorites are classified as stony meteorites, iron meteorites and stony iron meteorites, and further categorized according to their mineralogical content. They range in size from microscopic to many meters across. Of the several tens of tons of cosmic material entering Earth’s atmosphere each day, only about one ton reaches the ground.


24. Chondrites are a type of stony meteorite made mostly of iron- and magnesium-bearing silicate minerals. Chondrites are the most common type of meteorite, accounting for about 88% that fall to Earth. They originate from asteroids that never melted, or underwent differentiation. As such, they have the same elemental composition as the original solar nebula. Chondrites derive their name from the fact that they contain chondrules—small round droplets of olivine and pyroxene that apparently condensed and crystallized in the solar nebula and then accreted with other materials to form a matrix within the asteroid.


27. Regolith is a layer of loose material, including soil, subsoil and broken rock, that covers bedrock. On Earth’s moon and many other bodies in the solar system, it consists mostly of debris produced by meteorite impacts and blankets most of the surface.
At lower energy levels, the photoelectric effect, or Compton scattering, is prevalent. In this case, only a fraction of the gamma ray energy is deposited, and the rest leaves the material as low-energy photons. At higher gamma ray energy levels, above 3 MeV, pair production becomes dominant. Identification of elemental compositions is performed primarily by measuring the characteristic photoelectric energy of individual nuclear varieties when excited by an external radiation source, such as solar wind or other cosmic rays. At higher energy levels the pair-production mechanism generates well-defined spectra. As such, the most accurate GRS measurements were made during periods of high solar-flare activity when gamma ray energy levels were at their highest.

To improve the elemental identification capability of the GRS, an active detector cup shield was designed especially for NEAR. It was fabricated from a single bismuth germanate [BGO] crystal. The dense BGO cup acted as an active scintillator while providing direct and passive shielding from the local gamma ray environment and reducing unwanted background signals.

The GRS central detector assembly is based on a ruggedized thallium-activated [TI] sodium iodide [NaI] scintillator unit used in oilwell logging operations, designed and built by Schlumberger (below). NaI-based scintillators are widely used in downhole logging-tool applications to make measurements of density, natural radioactivity and elemental spectra. As an example, the EcoScope multifunction logging-while-drilling tool uses a NaI detector to make while-drilling spectroscopy measurements. Other logging tools use different materials.

Interactions of gamma rays with solid materials depend on the energy of the gamma rays and on the density and the atomic number of the materials being investigated. These interactions can be classified by the level of energy absorbed by the substrate material.

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The new design replaced the more expensive and less reliable long booms used in other missions to reduce unwanted signals from the activation of the spacecraft body itself by cosmic radiation. The GRS also provided sensitivity to the direction from which the gamma rays were coming.

**Detour to a C-Type Asteroid**

In early December 1993, NEAR mission managers at The Johns Hopkins University Applied Physics Laboratory reviewed a list of asteroids that might be in close proximity to NEAR’s flight path (next page, top). Asteroid 253 Mathilde was found to be within 0.015 AU, or about 2.25 million km [1.4 million miles], of NEAR’s planned orbital path. Engineers calculated that with slight changes in NEAR’s planned trajectory, it could encounter 253 Mathilde with only a 57 m/s [187 ft/s] change in velocity, well within the spacecraft’s velocity margin.

Although the dark asteroid was discovered in 1983, little was known about Mathilde. New astronomical observations from ground-based telescopes showed it to be a C-type asteroid with an unusual rotation period of 15 days, almost an order of magnitude slower than most other known asteroid rotation periods.

NEAR encountered Mathilde on the way to Eros after five trajectory-correction maneuvers about 2 AU from the Sun. At this distance, available power from the spacecraft’s solar-powered system was down nearly 75%. With this limited power, astronomers could use only the MSI to explore the surface of the asteroid, and radio-tracking data, before and after approach, to help determine the mass of the asteroid.

During the flyby, Mathilde exerted a slight gravitational pull on the NEAR spacecraft. Because of Mathilde’s mass, the gravitational effects on NEAR’s path were detectable in the spacecraft’s radio-tracking data.

Data from radio-tracking mass estimates along with volume approximations helped scientists calculate the asteroid’s approximate density of 1.3 ± 0.3 g/cm³ [81.16 ± 18.73 lbm/ft³]. Because of the asteroid’s spectra, Mathilde was believed to be similar in composition to carbonaceous-chondrite meteorites. However, Mathilde’s density was half of that expected, implying either a high internal porosity or significant void space within the asteroid.

Scientists imaged Mathilde over a 25-minute period during the spacecraft’s approach at a distance of 1,200 km [746 miles] and a speed of 9.93 km/s [22,213 mi/h]. A total of 534 images...
were obtained during this interval at resolutions ranging from 200 to 500 m [666 to 1,640 ft] (above).

Images obtained during the flyby of Mathilde show an asteroid with a heavily cratered surface. At least four giant craters have diameters that are comparable to the asteroid’s mean radius of 26.5 km [16.5 miles]. The magnitude of the impacts required to create craters of this size is significant. Scientists suspect that Mathilde did not break apart during any of these impacts because of the asteroid’s high porosity. Laboratory data suggest that cratering in highly porous targets is governed more by compaction of the target material than by fragmentation and excavation.22 Cratering processes governed by structural properties such as porosity produce craters with steep walls, crisp rims and with little ejecta, similar to those imaged on Mathilde.

The images also show Mathilde is remarkably uniform. The NEAR observations revealed no evidence of any regional albedo, or spectral variations, implying a homogeneous composition. Further, the measured albedo was consistent with ground-based telescopic observations.

Although significant data were gained by the Mathilde flyby, numerous questions about C-type asteroids remain unanswered. Mathilde’s density was inconsistent with common carbonaceous-chondrite meteorites found on Earth, and the asteroid’s surface appears homogeneous. So, the question remains: what connection, if any, exists between dark asteroids and meteors found in the solar system?

Detecting Gamma Ray Bursts

Gamma ray bursts (GRBs) have remained one of the great mysteries of astrophysics since their discovery more than 30 years ago. NASA’s Hubble Space Telescope made the first observation of an object associated with a GRB that was detected by the Italian BeppoSAX satellite in February 1997.31

Scientists believe that GRBs result from massive explosions in the distant universe that release waves of high-energy photons. GRBs seem to occur daily and emanate from random parts of the sky. GRBs represent the most powerful events known in the universe, emitting in one second as much energy as the Sun will emit in its lifetime. Spectroscopic analyses of faint, but long-lasting GRB optical afterglows have, in a number of cases, indicated Doppler shifts in the red spectrum that indicate a cosmological origin of GRBs.32 Time is critical in follow-up observation efforts, since GRB afterglows fade quickly, in the radio as well as optical spectrum, making it difficult for astronomers to locate the emission source.

29. Pair production is the chief method by which energy from gamma rays is observed in condensed matter. Provided there is enough energy available to create the pair, a high-energy photon interacts with an atomic nucleus and an elementary particle and its antiparticle are created.
Since 1993, astronomers have used specially instrumented spacecraft to help identify the source of GRBs. These include the Ulysses spacecraft and several spacecraft near the Earth: the BeppoSAX, Wind observatory, the Compton Gamma-Ray Observatory (CGRO) and the Rossi X-Ray Timing Explorer. Unfortunately, these near-Earth spacecraft are too close to each other to allow a definitive triangulation of burst locations.

The loss of the Pioneer Venus orbiter and Mars Observer in the early 1990s meant that astronomers lacked a third detector source for accurate triangulation of deep-space GRBs. The addition of the NEAR spacecraft to the interplanetary network greatly increased the probability of associating a GRB with a particular source using optical and radio telescopes.

The GRS onboard NEAR was not originally intended to begin its work until the spacecraft reached Eros. However, while en route to Eros, simple software changes to the XGRS system allowed scientists to use the spectrometer for GRB detection. By adding the NEAR spacecraft to the GRB interplanetary network (IPN) and taking advantage of significant improvements in telemetry rate and computational capability, NEAR helped reduce GRB detection and triangulation times from months to seconds.

As an example, gamma ray detectors on the NEAR and Ulysses spacecraft first recorded gamma ray burst GRB000301C on March 1, 2000. Initially, the sky coordinates of the burst were not well-defined, but with data from the NEAR and Ulysses spacecraft, an area of the sky about 4.2 arcminutes wide and 180 degrees in length was identified as the potential source. A second position from the Rossi X-Ray Timing Explorer reduced the error to 4.2 degrees long and 8.7 arcminutes wide. Triangulation of the three data points further narrowed the gamma ray emission zone to within a 50 arcminute square, thus allowing a much quicker search of the sky by the HST and ground-based telescopes.

Over a 15-month period from December 1999 to February 2001, the IPN, including NEAR, detected over 100 GRBs. Of these, 34 were localized rapidly and precisely enough to allow optical and radio telescope follow-up observations. The suspected GRB emission locations were determined with accuracies of the order of several arcminutes. One of the most interesting results was the detection of a GRB originating in the southern constellation Carina. Optical observations of an extreme red-shift indicated that the source of the GRB was about 12.5 billion light-years from Earth, making it the most distant GRB yet detected.

Unlocking the Secrets of Eros

The NEAR spacecraft entered Eros orbit on February 14, 2000, beginning its one-year mission to explore Eros. Orbital characteristics ranged from elliptical to circular and took NEAR within 35 km [22 miles] of the surface of Eros. Then, almost six years to the day after launch, engineers at JHUAPL brought NEAR’s mission to its culmination with a successful controlled descent to the surface of Eros.

Although the primary mission of NEAR was to investigate the mineralogy, composition, magnetic fields, geology and origin of Eros, NEAR obtained much more detailed information during its orbital encounter with Eros.

Images, laser altimetry and radio-science measurements provided strong evidence that Eros is a consolidated, yet fractured asteroid with a regolith cover varying dramatically in depth from near zero to as much as 100 m [328 ft] in some areas. Scientists believe that the presence of joined and well-defined craters is indicative of cohesive strength within the asteroid. Surface images show the geometric relationship of grooves and cuts in the surface, suggesting that the rock is competent and not a loosely bound agglomeration of smaller rocks.

The gravity field on Eros appeared to be consistent with that expected from a uniformly-density object of the same shape. The measured density of Eros indicates that it has a bulk porosity of 21 to 33%, implying that even though the asteroid’s mass is uniformly distributed, it is significantly porous and potentially fractured, but to a lesser extent than Mathilde.

Imaging at resolutions of a few centimeters per pixel revealed a complex and active regolith that has been significantly modified and redistributed by gravity-driven slope processes. High-albedo features noted in images taken around crater walls that slope in excess of 25° were often 1.5 times brighter than their surroundings, indicating recent changes in surface characteristics due to regolith sloughing (above right).

Silicate mineralogy analysis performed by the NIS was consistent with ordinary chondrite meteorites. Spatially resolved measurements of the asteroid’s surface provided no evidence for mineral compositional variation. Scientists believe that the spectral uniformity of Eros may have resulted from a uniformly high degree of space weathering caused by micrometeorite bombardment.

The NEAR spectrographs, XRS, GRS and NIS measured the elemental and mineral composition of Eros. Data acquired by the XRS during orbiting showed calcium, aluminum, magnesium, iron and silicon abundances consistent with ordinary chondrite and certain primitive achondrite meteorites. However, the level of sulfur typical of chondritic meteorites was absent or depleted on Eros.

Although the surface of Eros appears to be elementally homogeneous, the XRS instrument can measure only surface composition, so it is unknown if the sulfur depletion is a surface effect or consistent through the core of the asteroid. If the sulfur depletion is consistent across the bulk of the asteroid, this would imply an association with primitive achondrite meteorites.

The orbital GRS measurements had lower signal levels than predicted, so the elemental ratios with the highest precision were measured after landing. GRS data showed the Mg/Si and Si/O ratios and the abundance of K to be consistent with chondritic meteorite values, but found Fe/Si and Fe/O levels to be lower than what would be expected with chondritic meteorites. Since these measurements were
made after landing and the GRS instrument can probe tens of centimeters below the surface, these measurements reflect a volume of about 1 m$^3$ [35.3 ft$^3$] around the detector. From the GRS data alone, scientists could not determine whether the Fe depletion is a global compositional property of Eros or a localized property of the landing zone.

Although the XGRS system observed Eros during a one-year orbital period, the useful time for data collection was considerably shorter. Engineers were limited by the angular requirements of the solar panels relative to the sun, telemetry time and periods when the surface of Eros was properly lit by the Sun. In the end, scientists found that the best quality compositional data were acquired during low-altitude orbits and after landing on Eros (right). Once NEAR was on the surface, the gamma ray spectrometer obtained in-situ measurements of the regolith for a period of about 14 days.\(^{39}\)

The surface composition of Eros suggests that the asteroid is similar in bulk composition to a range of meteorites that have experienced minimal thermal alteration since their formation at the birth of the solar system. Scientists believe that Eros is primitive in its chemical composition and has not experienced differentiation into a core, mantle and crust. Differences between XRS and GRS data in Fe/Si ratio and an apparent deficiency of sulfur at the surface of Eros could reflect either alteration processes in the regolith during the last millions to billions of years or partial melting in the first 10 million years of solar system history.

These spectral measurements provided scientists with a new set of questions. While the spectral observations are consistent with an ordinary chondritic meteorite composition, the measurements did not establish an undisputed link between Eros and a specific meteorite type. The question remains whether Eros is unrelated to any known meteorite type, or is actually a chondrite type at depth, below the surface layers that may have been altered by weathering processes.

Scientists were surprised that Eros appears to have little or no magnetic field. Most meteorites, including chondrites, tend to be more magnetized than Eros. Perhaps its low levels of iron and the fact that it never has been heated to melting play a role in this differentiation. The spectral homogeneity of Eros combined with gravity-field measurements, structural characteristics and indications of structural coherence suggests that Eros is a collisional fragment of a larger parent body.

The NEAR mission, a mission of many firsts in NASA’s Discovery Program, substantially increased our knowledge of primitive bodies in our solar system. Although the data returned by NEAR have revealed many secrets of asteroids, many questions remain unanswered, and more will be learned from future missions.

Exploring Gas Giants

The goal of the Cassini mission is to explore Saturn, its many known moons and those yet to be discovered. Managed by NASA’s Jet Propulsion Laboratory (JPL) in Pasadena, California, USA, Cassini is a joint endeavor of NASA, the European Space Agency (ESA) and the Italian space agency, Agenzia Spaziale Italiana (ASI). It is one of the most ambitious efforts in planetary space exploration.

Because of the low level of sunlight reaching Saturn, solar arrays are not feasible as a power source. Engineers employed a set of radioisotope-thermoelectric generators similar to those used...

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4-m high-gain antenna

11-m magnetometer boom

Radio/plasma wave subsystem antenna (1 of 3)

Remote sensing instruments

445 N engine (1 of 2)

Huygens Titan probe

Radar bay

HDAC

FUV spectrograph

Low-gain antenna (1 of 2)

Remote sensing instruments

GPM engine (1 of 2)

Radar bay

Huygens Titan probe

Radioisotope thermoelectric generator (1 of 3)

^ Preparing Cassini for flight. Technicians reposition and level the Cassini orbiter in the Payload Hazardous Servicing Facility at the Kennedy Space Center in July 1997, after stacking the craft’s upper equipment section on the propulsion module (left). The orbiter’s primary systems are shown (right). (Images courtesy of NASA/JPL.)

^ Imaging Saturn’s rings. The Ultraviolet Imaging Spectrograph (UVIS) is a set of telescopes used to measure ultraviolet light from the Saturn system’s atmospheres, rings and surfaces. The UVIS has two spectrographic channels or instruments: the extreme ultraviolet channel and the far ultraviolet (FUV) channel. Each instrument is housed in aluminum cases, and each contains a reflecting telescope, a concave grating spectrometer and an imaging, pulse-counting detector. The UVIS also includes a high-speed photometer (HSP) channel, a hydrogen-deuterium absorption cell (HDAC) channel and an electronic and control subassembly. (Image courtesy of NASA/Laboratory for Atmospheric and Space Physics.)
on the previous Galileo and Ulysses missions. With these systems, heat from the natural decay of plutonium-238 is used to generate electricity to operate Cassini's systems.

The Cassini spacecraft is equipped with 18 instruments, 12 on the orbiter and another six on the Huygens probe, which is designed to separate from the main spacecraft and parachute through the atmosphere of Titan, Saturn's largest moon. The 12 instruments on the orbiter are currently conducting in-depth studies of Saturn, its moons, rings and magnetic environment.

Key to Cassini's science mission is the Ultraviolet Imaging Spectrograph (UVIS), an instrument based on Schlumberger sensors and packaging, and designed to operate in harsh environments like those found in oil and gas logging operations. The UVIS is now helping scientists determine atmospheric chemistry, the nature of clouds and ring systems, and the atmospheric energy balance on Saturn and its moon Titan.

The UVIS comprises a set of telescopes that measure ultraviolet light from the Saturn system's atmospheres, rings and surfaces. The instrument has two spectrographs: the far ultraviolet channel (FUV), 110 to 190 nm, and the extreme ultraviolet channel (EUV), 56 to 118 nm.

The FUV and EUV channels in the UVIS spectrometer require different detectors to optimize sensitivity to the wavelength range required by the Cassini project. In cooperation with the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado, Schlumberger designed the detector response to meet these requirements.

The FUV detector was assembled using a cesium iodide photocathode with a magnesium fluoride window. This detector was vacuum-sealed and included an integrated pump that maintained an ultrahigh vacuum during the spacecraft assembly and launch. Once in space, the detector was equalized to the vacuum of space for the voyage to Saturn.

The EUV detector utilizes a potassium bromide photocathode and has no window since transmission of all known substances is very poor in this short wavelength range. Fortunately, potassium bromide is a very robust photocathode and can be exposed to dry air for the short time required for testing and assembly. Once in the vacuum of space, the detector cover was opened, allowing light to enter the instrument.

Both detectors utilize specially selected microchannel plates (MCP). MCP technology has a long history in spaceflight imaging instruments. Quality-control procedures during manufacturing allowed only MCPs with very low-defect densities to be used for final assembly. Once an MCP was available, LASP and Schlumberger scientists worked together during the final assembly process. The units were then transported to NASA laboratories for final testing.

Two FUV and two EUV detectors that met the stringent quality requirements for space travel to Saturn were assembled at the Schlumberger Princeton Technology Center (PTC) in New Jersey. One pair of detectors was designated as flight units while the second set was kept in reserve as a backup.

The UVIS also includes a high-speed photometer (HSP) channel, a hydrogen-deuterium absorption cell (HDAC) channel and electronic and control subassemblies. Scientists are using the HSP to make stellar occultation measurements of the structure and density of material in Saturn's rings.

Cassini was launched on October 15, 1997, from Cape Kennedy, Florida, aboard a Titan IVB/Centaur rocket, the most powerful launch vehicle in the US fleet. After Cassini was placed in orbit around Earth, the upper stage fired to send Cassini on an interplanetary trajectory that would eventually deliver the spacecraft to Saturn.
Cassini flew twice past Venus, then once past Earth and Jupiter. The spacecraft’s speed relative to the Sun increased as it approached and swung around each planet, giving Cassini the cumulative boost it needed to reach Saturn with minimal fuel consumption. After reaching Saturn, Cassini fired its main engine for about 96 minutes, reducing the spacecraft’s speed and allowing it to be captured in an orbit around Saturn. On January 5, 2005, Cassini released the European-built Huygens probe toward Titan.

Journey to a Distant Moon
With a diameter larger than the planet Mercury, Titan is one of the most interesting moons in the solar system. The surface of this moon lies hidden beneath an opaque atmosphere more than 50% denser than that of Earth (left).

Titan’s atmosphere is filled with a brownish-orange haze composed of complex organic molecules falling like rain from the sky to the surface. Most scientists agree that conditions on Titan are too cold for life to have evolved—although there are theories concerning the possibility of life forms in covered lakes of liquid hydrocarbons warmed by the planet’s internal heat.

The Huygens probe entered Titan’s atmosphere on January 14, 2005, deployed its parachutes and began its scientific observations during a descent through the moon’s dense atmosphere lasting close to 2½ hours (below left). Instruments onboard the probe detected a surface temperature of 94K at the landing site. Images taken by the probe while descending showed surface channels that appeared to indicate rain or fluid flow, possibly in the form of liquid methane. Ridges as tall as 100 m were observed near the landing area (next page, top).

High quantities of methane were detected in the lower atmosphere, with nitrogen predominating in the upper atmosphere. Oxygen was not detected probably because it is tied up as frozen water. This would also prevent the formation of carbon dioxide.

Laboratory tests recreated the impact measurements derived from the onboard penetrometer. These tests indicate that the surface in the landing area may be composed of fine particles with a thin crust. Accelerometer measurements suggest the probe settled 10 to 15 cm [4 to 6 in.] into the surface. Heat from instruments then evaporated liquid methane in the soil and released it around the spacecraft as methane gas. The Huygens probe continued...
making measurements and transmitting data to Cassini for 72 minutes after landing until power limitations and deterioration of the spacecraft due to extreme surface conditions on Titan resulted in loss of signal.

Exploring the Ringed Planet
Aside from Titan, more moons of greater variety orbit Saturn than any other planet. So far, observations from Earth and by spacecraft have found Saturnian satellites ranging from small asteroid-size bodies to those as large as Titan.

Saturn is the second-largest planet in the solar system. Like the other gaseous outer planets—Jupiter, Uranus and Neptune—it has an atmosphere made up mostly of hydrogen and helium, and like them, it is ringed. Saturn’s distinctive bright rings are made up of ice and rock particles ranging in size from grains of sand to small houses.

Although the face of Saturn appears calm, the planet has a windswept atmosphere where an equatorial jet stream blows at 1,800 km/h [1,118 mi/h], and swirling storms churn beneath the cloud tops. Early explorations by NASA’s Pioneer 11 spacecraft in 1979, and the Voyager 1 and 2 spacecraft in 1980 and 1981, found Saturn to have a huge and complex magnetic environment where trapped protons and electrons interact with each other, the planet, the rings and the surfaces of many of Saturn’s moons.

From Earth, Saturn’s rings appear as only a few monolithic bands, while in reality, they consist of thousands of rings and ringlets, with particles sometimes arranged in complicated orbits by the gravitational interaction of small moons previously unseen from Earth (right). Scientists are using data from the UVIS in detailed computer models to simulate the complex motion of these rings.

Second in size only to Jupiter, Saturn has more than 750 times the volume of Earth. Combined with the planet’s low density, less than half that of water, its fast rotation promotes a bulge of material near the equator. Saturn is shaped like a flattened ball; its pole-to-pole diameter is only 108,728 km [67,560 miles], compared to about 120,536 km [about 74,898 miles] for the equatorial diameter.

Unlike rocky inner planets such as Earth, Saturn has no surface on which to land. A spacecraft descends into its atmosphere would simply find the surrounding gases becoming denser, and the temperature progressively hotter; eventually the craft would be crushed and melted. Detailed analysis of Saturn’s gravitational field leads astronomers to believe that the deepest interior of Saturn must consist of a molten rock core about the same size as the planet Earth, but much denser.

Spectroscopic studies by the Voyager spacecraft found Saturn to be made up of about 94% hydrogen and 6% helium. Hydrogen and helium are the primary constituents of all the giant gas planets, the Sun and the stars. Gravity at the top of Saturn’s clouds is similar to that near the surface of Earth. The temperature near the cloud tops is about -139°C [-218°F], increasing toward the planet’s core due to increased atmospheric pressure. At the core, Saturn’s temperature is predicted to be about 10,000°C [18,000°F].

On June 21, 2005, the UVIS detected auroral emissions from both Saturn’s northern and southern poles (above right). These emissions are believed to be similar to Earth’s Northern Lights yet are invisible to the naked eye. Ultraviolet images captured the entire oval of the auroral emissions from hydrogen gas excited by electron bombardment. Time-lapse images indicate that aurora lights are dynamic, responding rapidly to changes in the solar wind.

New Moons
There were only 18 known moons orbiting Saturn when the Cassini spacecraft began its mission to Saturn in 1997. During Cassini’s seven-year journey, Earth-based telescopes uncovered 13 more moons. Soon after the spacecraft reached Saturn, the Cassini team discovered two more tiny moons, Methone and Pallene. The two new moons are approximately 3 km [1.8 miles] and 4 km [2.5 miles] across.

Scientists suspected that more tiny Saturnian moons might be found within the gaps in Saturn’s rings. On May 1, 2005, using a sequence of time-lapse images from Cassini’s cameras, astronomers confirmed the presence of a tiny moon hidden in a gap in Saturn’s A ring. The images show the tiny object in the center of the Keeler Gap and the wavy patterns in the gap edges that are generated by the moon’s gravitational influence (above).

The new object, Daphnis, is about 7 km [4 miles] across and reflects about 50% of incident sunlight. Scientists predicted the moon’s presence and its orbital distance from Saturn after July 2004, when they saw perturbations in the ring structure of the Keeler Gap’s outer edge. These images were obtained with the Cassini spacecraft narrow-angle camera on May 1, 2005, at a distance of approximately 1.1 million km [680,000 miles]. (Image courtesy of NASA/JPL/Space Science Institute.)

Signs of an Atmosphere
Although the moon Enceladus is covered with ice composed of water, like Saturn’s other moons, it displays an abnormally smooth surface with very few impact craters. With a diameter of about 500 km [310 mi], Enceladus would fit into the state of Arizona. Yet despite its small size, Enceladus exhibits one of the most interesting surfaces of all the icy satellites. Enceladus reflects about 90% of the incident sunlight as if

44. NASA/Jet Propulsion Laboratory, reference 43.
covered with fresh-fallen snow, placing it among the most reflective objects in the solar system. Although Enceladus was previously thought to be a cold and dead rock mass, data from the Cassini spacecraft indicate evidence of ice volcanism, which might explain its smooth surface features.

In July 2005, Cassini’s instruments detected a cloud of water vapor over the moon’s southern pole and warm fractures where evaporating ice probably supplies the vapor cloud. So far, Enceladus is the smallest body found that displays evidence of active volcanism. Scientists theorize that warm spots in the moon’s icy and cracked surface are probably the result of heat from tidal energy like the volcanoes on Jupiter’s moon Io. Its geologically young surface of water-base ice, softened by heat from below, resembles areas on Jupiter’s moons, Europa and Ganymede.

Cassini flew within 175 km [109 miles] of Enceladus on July 14, 2005. Data collected during that flyby confirm an extended and dynamic atmosphere. This atmosphere was first detected by Cassini’s magnetometer during a distant flyby earlier in 2005 (above left).

Cassini’s magnetometer detected disturbances in the magnetic field caused by small currents of ionized gas from the atmosphere around this moon. These could be detected by the instrument long before imaging instruments could be applied to confirm this finding.

As Cassini approached this small body, imaging instruments were able to make measurements that showed gas composition, further confirming the presence of an atmosphere. The ion and natural mass spectrometers and the UVIS showed that the southern atmosphere contains water vapor (left). The mass spectrometer found that water vapor comprises about 65% of the atmosphere, with molecular hydrogen at about 20%. The rest is mostly carbon dioxide and some combination of molecular nitrogen and carbon monoxide. The variation of water-vapor density with altitude suggests that the water vapor may come from a localized source comparable to a geothermal hot spot. The ultraviolet results strongly suggest a local vapor cloud. The fact that the atmosphere persists on this low-gravity world, instead of instantly escaping into space, suggests that the moon is geologically active enough to replenish the water vapor at a slow, continuous rate.

High-resolution images show that the south pole has an even younger and more fractured appearance than the rest of Enceladus, complete
with icy boulders the size of large houses and long, bluish cracks or faults (left).

Another Cassini instrument, the composite infrared spectrometer (CIRS), demonstrates that the southern pole is warmer than anticipated (below left). Temperatures near the equator were found to reach a frigid 80K. Scientists believe that the poles should be even colder because of the low level of energy received from the Sun. However, south polar average temperatures reached 85K, much warmer than expected. Small areas of the pole, concentrated near the fractures, are even warmer: higher than 140K in some places.

Scientists find the temperatures difficult to explain if sunlight is the only heat source. More likely, a portion of the polar region, including observable fractures, is warmed by heat escaping from the interior. Evaporation of this “warm” ice at several locations within the region could explain the density of the water-vapor cloud detected by Cassini’s instruments. How a 500-km [310-mile] diameter moon can generate this much internal heat and why it is concentrated at the southern pole are still a mystery.

Similar to multiple well-logging instruments working together deep beneath the Earth’s surface, the discovery of an atmosphere on Enceladus resulted from an array of different sensors working in synergy to acquire data and maximize scientific value.

The Challenge of Space
Advances in technology, particularly during the last 100 years, have helped change the way we view the Earth, our solar system and the universe beyond. From the E&P industry’s early beginnings, engineers, geoscientists and many other dedicated men and women have led the way in exploration of our inner space environment. Today, this same innovative spirit, and in many cases, similar technologies, are taking us beyond the confines of Earth’s environment into the vast unknowns of outer space.

The examples presented in this article are just a few of the contributions made by the oilfield service industry to space exploration. In the future, we can expect to see more terrestrial technology applied in the quest for extraterrestrial understanding. The late astrophysicist Carl Sagan wrote, “Imagination will often carry us to worlds that never were. But without it, we go nowhere.” It is this imagination and creativity that have driven the E&P industry to explore deep beneath the Earth’s surface and that will inevitably launch the first drilling expeditions to Mars and beyond. —DW